Fermilab

Tevatron Status

UTev Seminar

June 6, 2003

Mike Martens

V. Shiltsev, J. Annala, K. Bishofberger, B. Hanna, P. Ivanov, R. Moore, V. Ranjbar, J. Steimel, D. Still, C.Y. Tan, R. Tokarek, J. Volk, A. Xiao, X. Zhang, M. Syphers, Y. Alexahin, V. Lebedev, J. Johnstone, M. Xiao, N. Gelfand, L. Michelotti, D. Edwards, T. Sen, B. Erdelyi, A. Drozhdin, N. Mokov, P. Bauer

Talk Outline

Introduction to luminosity and the Tevatron.

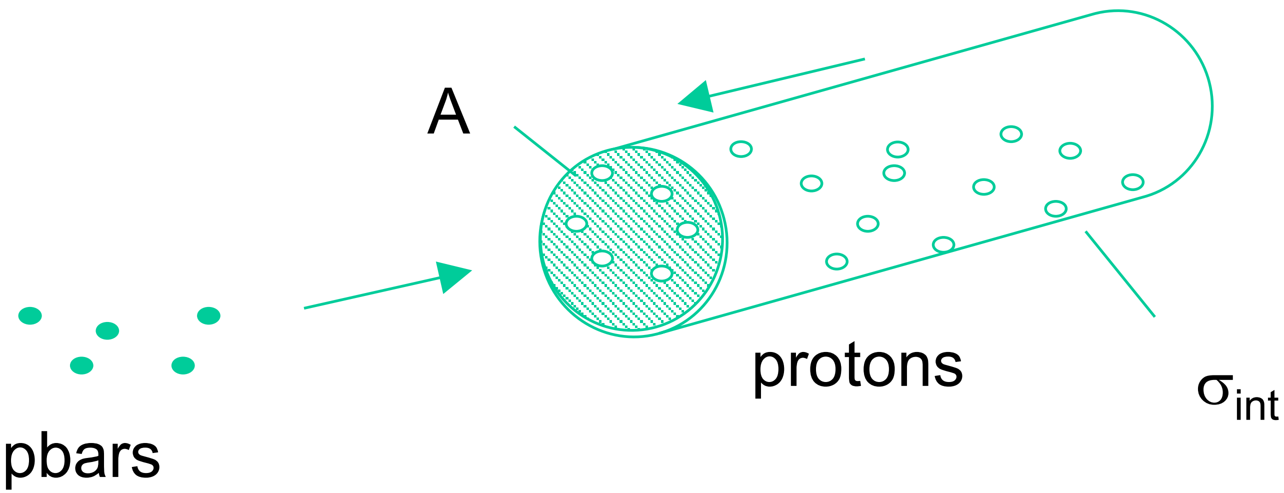
Recent performance of the Tevatron.

Tevatron physics issues.

Plans for the near future.

Luminosity

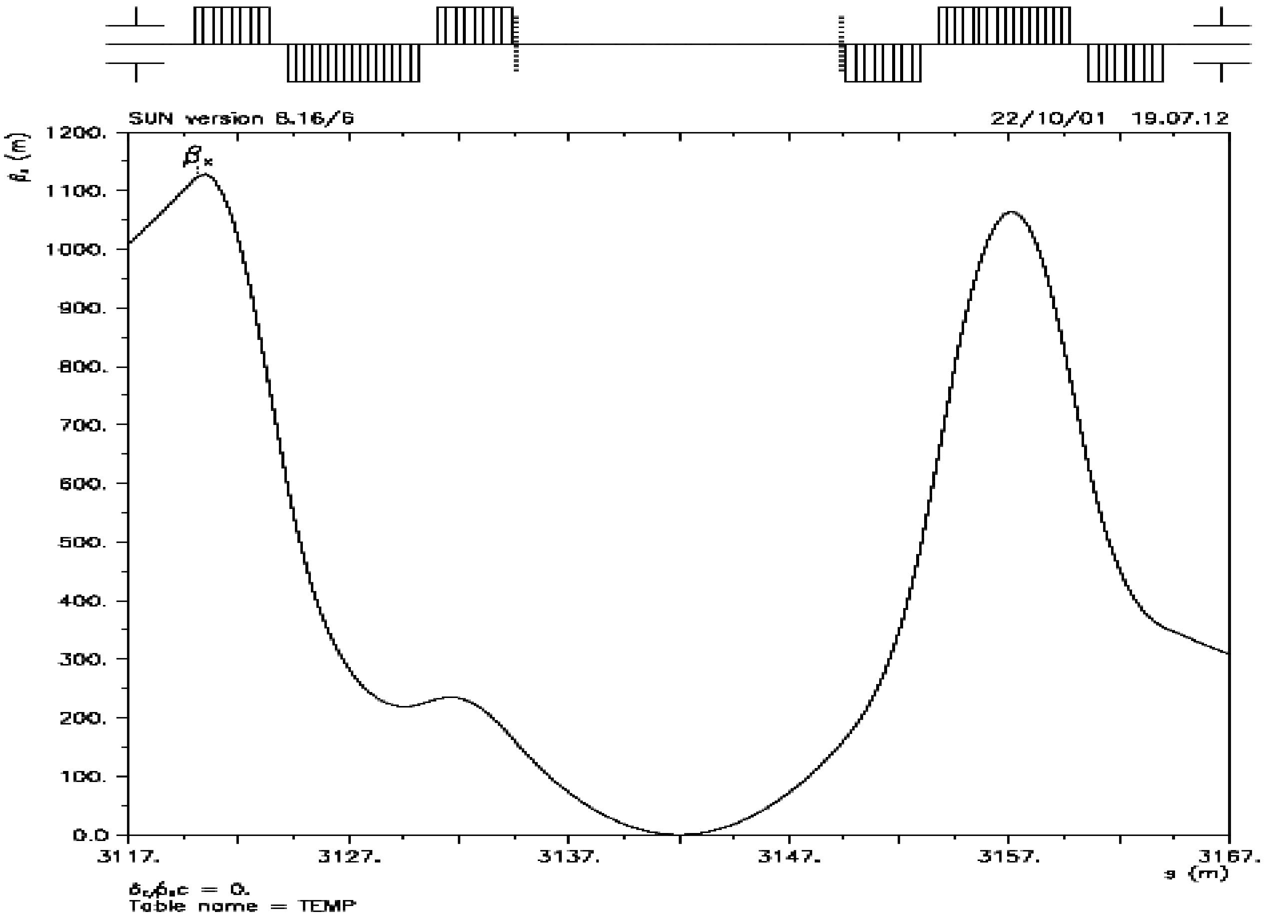
$$\text{Rate} = \mathcal{L}\ \sigma_{int}$$



$$P_{int} = N_{prot}\sigma_{int}/A$$

$$\mathcal{L} = f_{rev} N_{pbar} N_{prot}/A$$

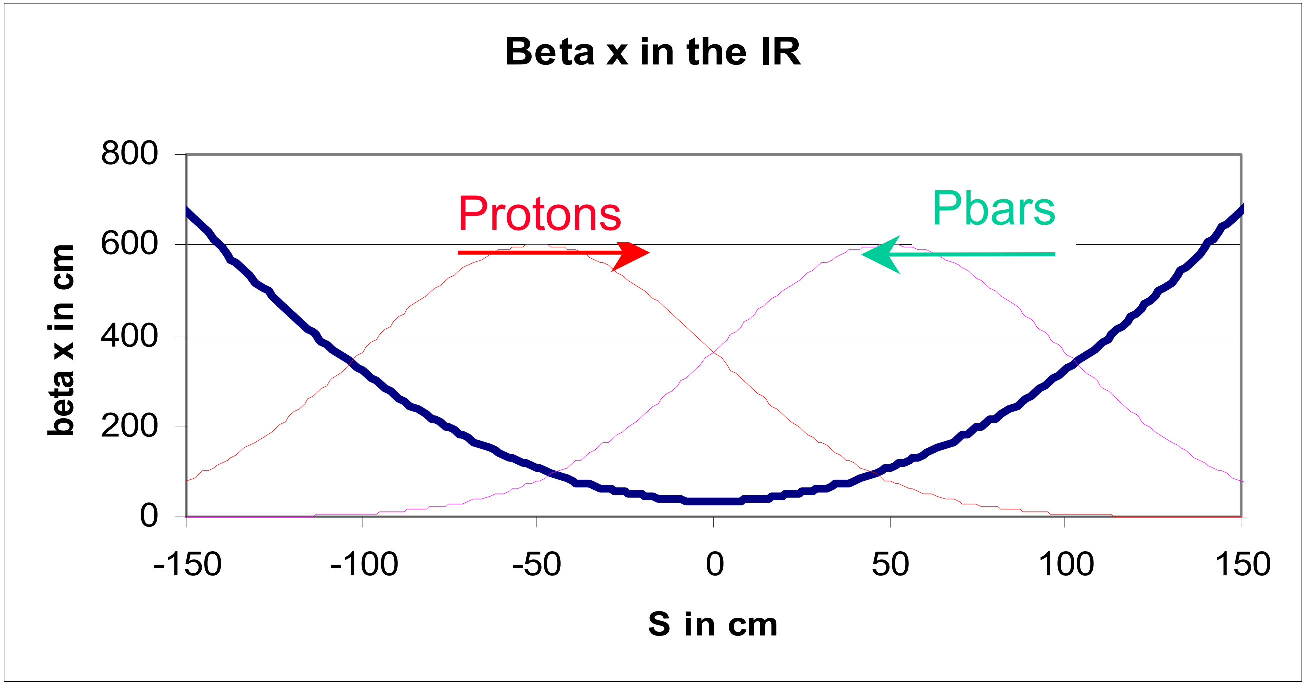
Low Beta Lattice



Hourglass shape

$$\beta_x = \beta_x^* + (s-s_0)^2/\ \beta_x^*$$

$$\sigma_x^2 = \varepsilon_x * \beta_x(s)$$



For 20 π mm-mrad emittance,
$\sigma_x = 31\ \mu$m (rms).

Luminosity Integral

$$\mathcal{L} = 2\, f_{rev} \iiiint \rho_1\, \rho_2\;\; dx\, dy\, dz\, d(ct)$$

$$\rho(x,y,z,ct) = \frac{N_1}{\sqrt{2\pi}\,\sigma_x} \exp[-\,(x+\Delta x/2)^2/\,2\,\sigma_x^{\,2}]$$

$$\frac{1}{\sqrt{2\pi}\,\sigma_y} \exp[-\,(y+\Delta y/2)^2/\,2\sigma_y^{\,2}]$$

$$\frac{1}{\sqrt{2\pi}\,\sigma_z} \exp[\,-(z+ct-ct_0)^2/\,2\sigma_z^{\,2}]$$

Hourglass shape:
$\sigma_x^{2} = \varepsilon_x * \beta_x(z)$
$\sigma_y^{2} = \varepsilon_y * \beta_y(z)$

Cogging offset:
center of beams
collide at $z = ct_0/2$

Separated Orbits:
$\Delta x = z \tan(\theta_x) + \Delta x_o$
$\Delta y = z \tan(\theta_y) + \Delta y_0$

Luminosity Formula

$$\boldsymbol{L} = \frac{f_{rev}\, B N_p N_{\bar{p}}}{2\pi\, \beta^* \,(\varepsilon_1 + \varepsilon_2\,)} \; F(\sigma_z / \beta^*, \theta_x, \theta_y)$$

Major limitations:

N_p / ε_1 = Protons beam brightness
(Beam-beam tune shift.)

$BN_{\bar{p}}$ = Total number of antiprotons
(Stacking rate.)

β^* = 35 cm is fixed by lattice.
$\varepsilon \cong 20\pi$ mm-mrad (95%, normalized).
σ_z = Bunch length.
B = Number of bunches.
θ_x, θ_y = Crossing angles (during 132 nsec operations.)

F = Form factor ≤ 1 for 36 x 36
= ~0.5 for 132 nsec.

Factors in the luminosity integral:

- Beam Intensities

  N_{prot}, N_{pbar}

- Beam Emittances

  ε_x, ε_y, σ_z, $\sigma_{,\Delta p/p}$ (Proton)

  ε_x, ε_y, σ_z, $\sigma_{\Delta p/p}$ (Pbar)

- Lattice Functions

  β^*_x, α^*_x, η^*_x, η'_x

  β^*_y, α^*_y, η^*_y, η'_y

- Separated orbits

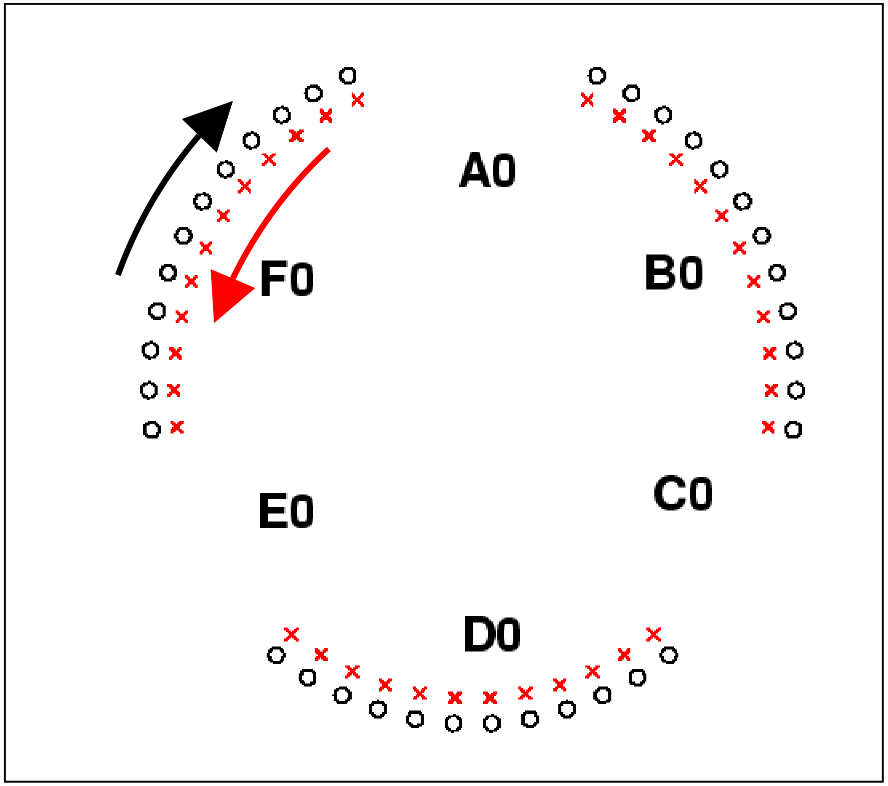
  Δ_x, θ_x, Δ_y, θ_y

- Cogging offset, revolution frequency

  ct_0, frev

24 factors in the luminosity integral!

Run II Bunch Configuration



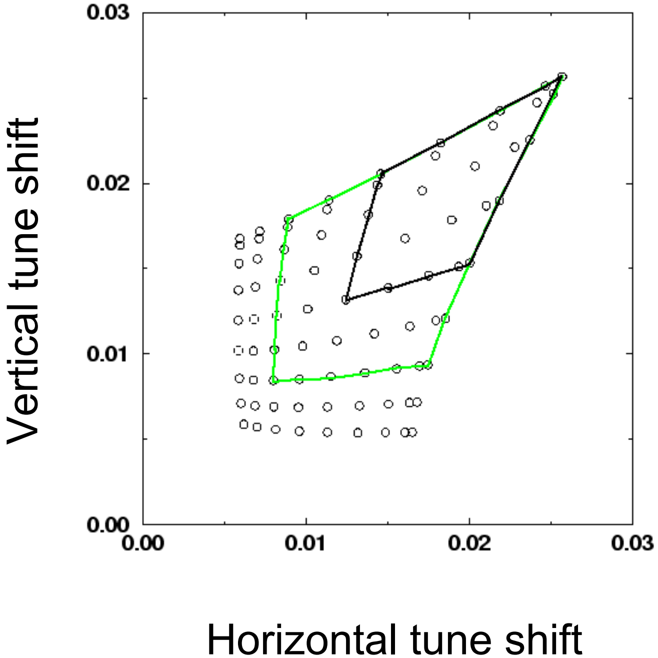
36 x 36 configuration

396 nsec bunch spacing

3 x 12 proton bunches

3 x 12 pbar bunches

Beam-beam tune shifts

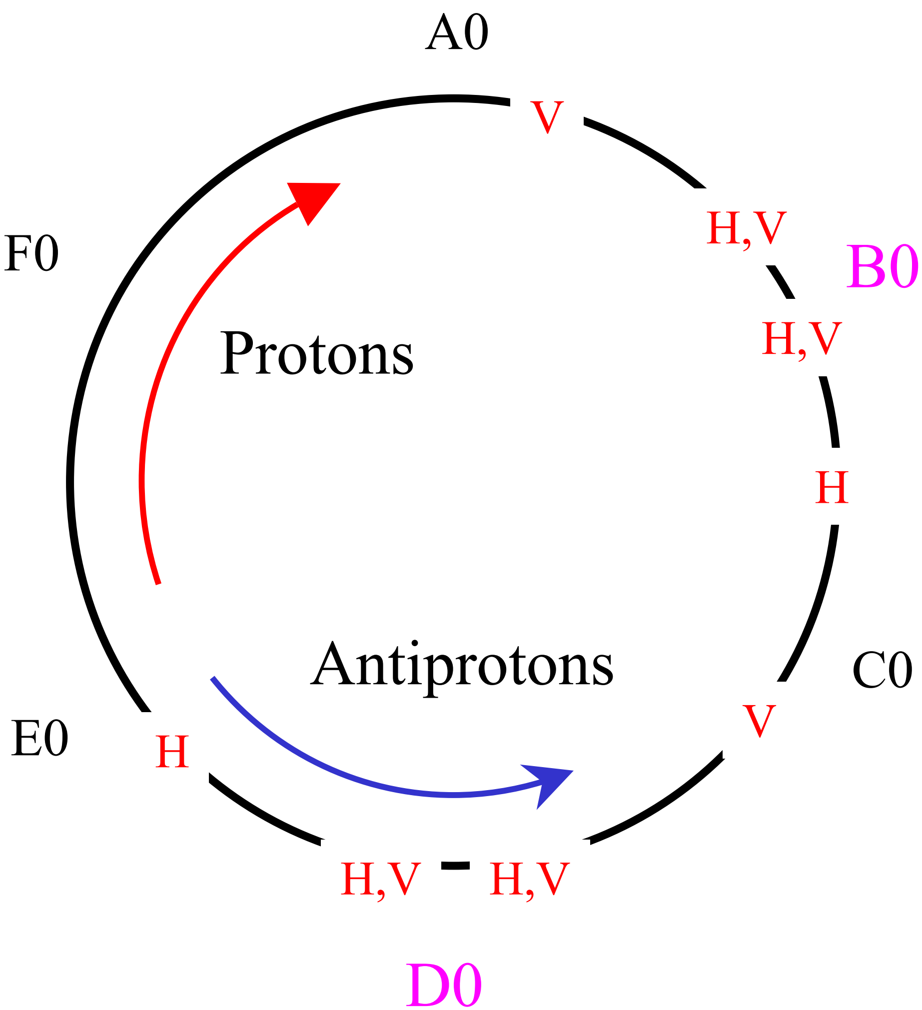


Tune Shift of a pbar bunch from 2 head on collisions

Tune shift becomes too large with more than 2 head-on collisions.

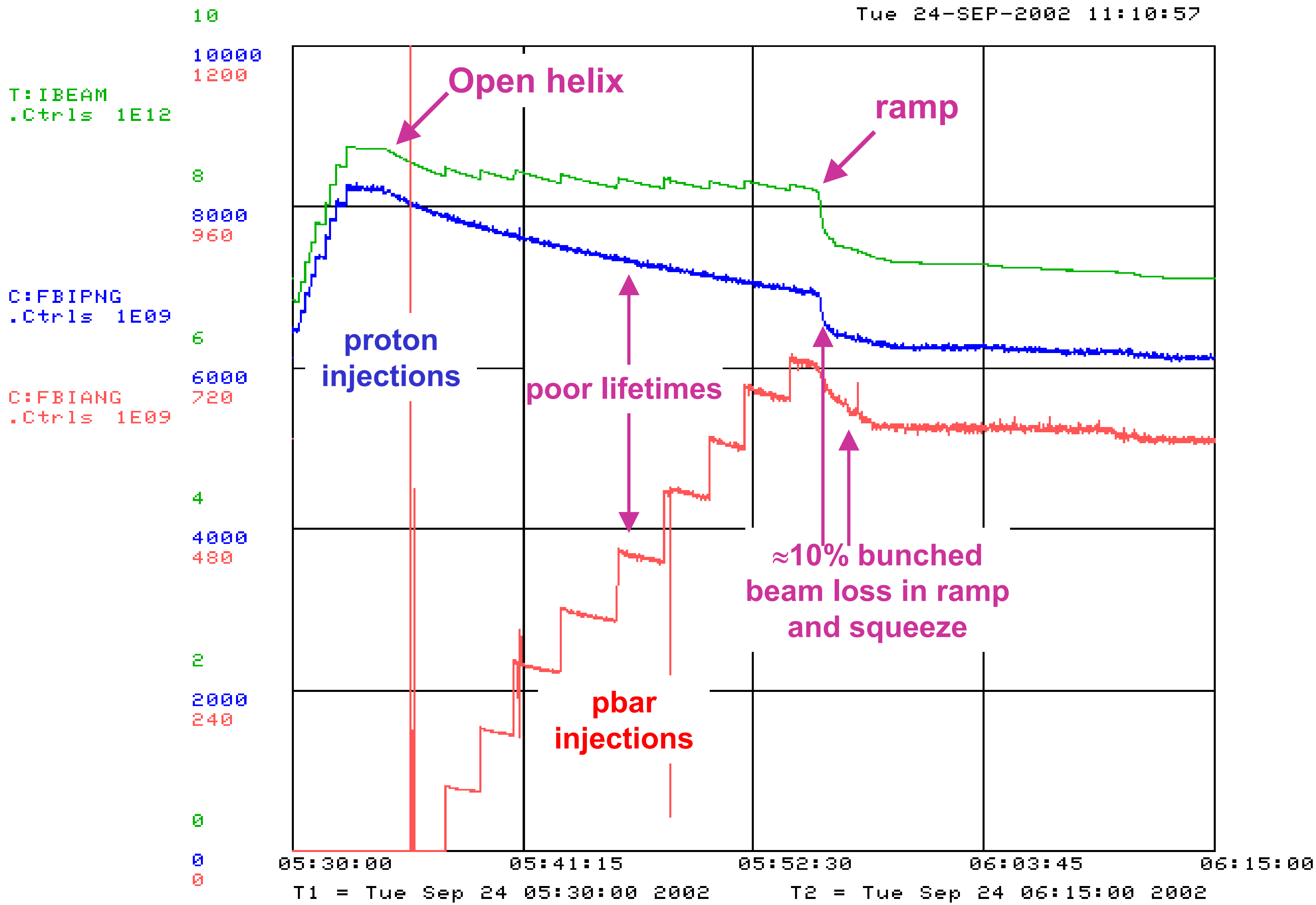
Solution is electrostatic separators.

Tevatron Separators

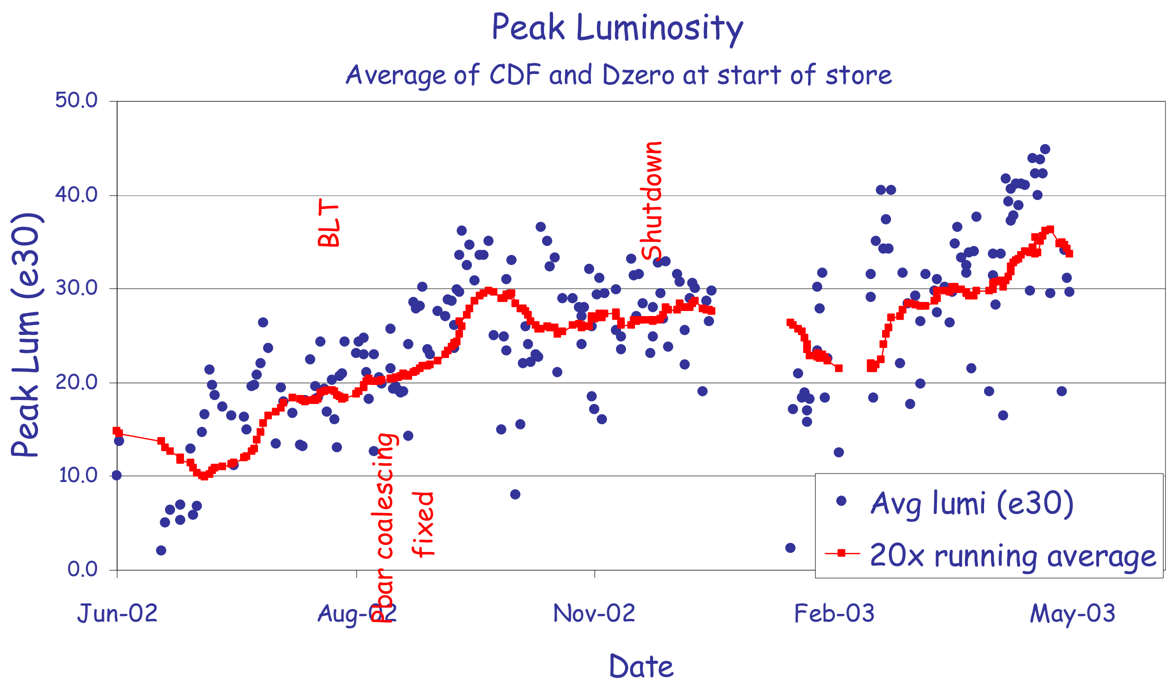


Electrostatic separators are used to separate the proton and pbar orbits transversely
…
except at the IPs where the protons and pbars collide head-on.

Tevatron Efficiencies

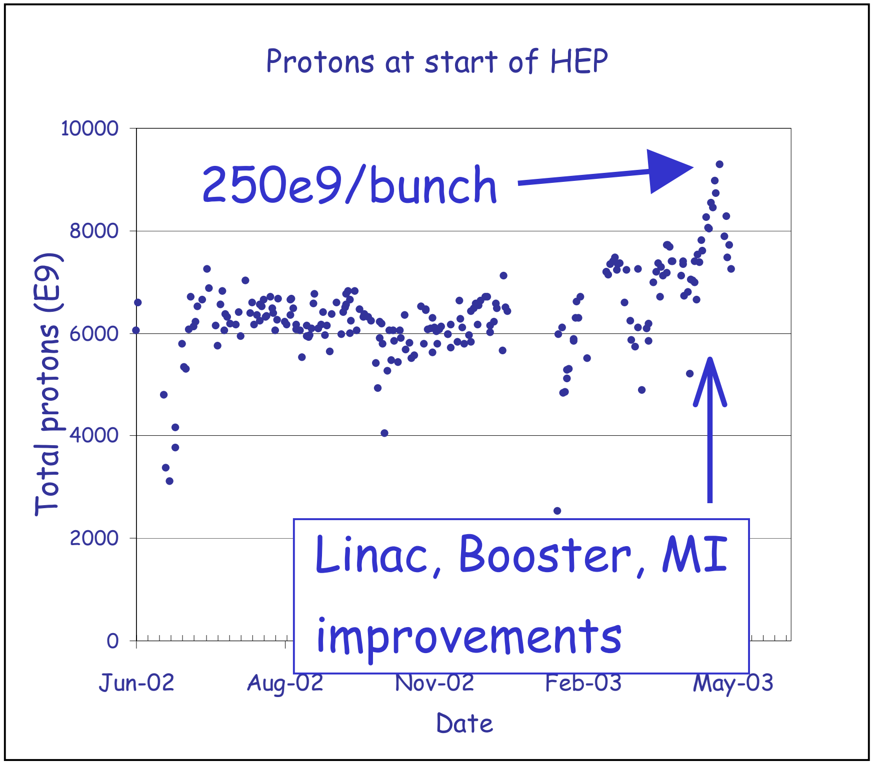


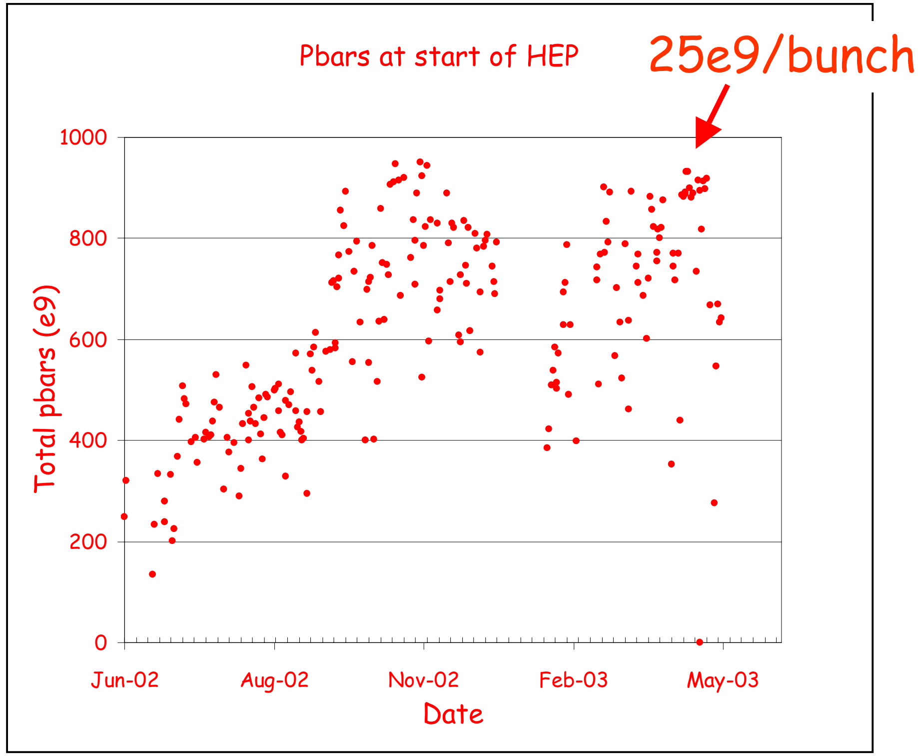
Luminosity Since June 2002



- 225 HEP stores
- 212 pb^{-1} to each detector
- Increase in luminosity from 15e30 to 40.5e30
- Run I record of 25.0e30 broken on 7/26/2002
- Run II record of 44.8e30 set on 5/17/2003

Beam Intensities





<u>Number of protons</u>

Mostly steady

in the 200e9 range ⇒ 250e9 max

<u>Number of antiprotons</u>

Increase factor of 2.5 Oct ⇒ March

from 9e9 ⇒ 25e9 per bunch

Tevatron Emittance

General comments on emittance blow-up from Flying Wire measurement**
(95%, normalized emittances):

- < 1π - 2π at proton injection
- ~ 5π - 6π at pbar injection
- < (negative) 2π - 3π protons at 150 (scraping)
- ~ (negative) 0π -3π pbars at 150 (scraping)
- 4π -7π blowup on ramp (prots and pbars)
- occasional instability, 5π – 50π, at 980 Gev

** There remains uncertainty of FW emittance measurements. (See later slides)

Reasons for *L*-progress Since Jun'02

• "Shot lattice"	AA	x 1.40
• Pbar emittance at injection Tev/Lines		x 1.20
• Pbar coalescing improvement	MI	x 1.15
• Shoot from larger stacks		x 1.10
• Improved Tev Pbar efficiency		x 1.10
• More Protons at Low Beta		x 1.10
	total	x 3.3

....plus additional improvements in the Tevatron:

- Tunes/coupling/chromaticities at 150/ramp/LB
- Orbit smoothing
- Longitudinal dampers to stop σ_s blowup
- Transverse dampers improves 150 Gev lifetime
- F11 vacuum

Goals and Current Performance

Parameter	Current Status	Record Store	FY03 Goal	
Typical Luminosity	3.5e31	4.5e31	6.6e31	$cm^{-2}sec^{-1}$
Integrated Luminosity	6.0		12.0	pb^{-1}/week
Protons/bunch	200e9	240e9	240e9	
Antiprotons/bunch	22e9	25e9	31e9	

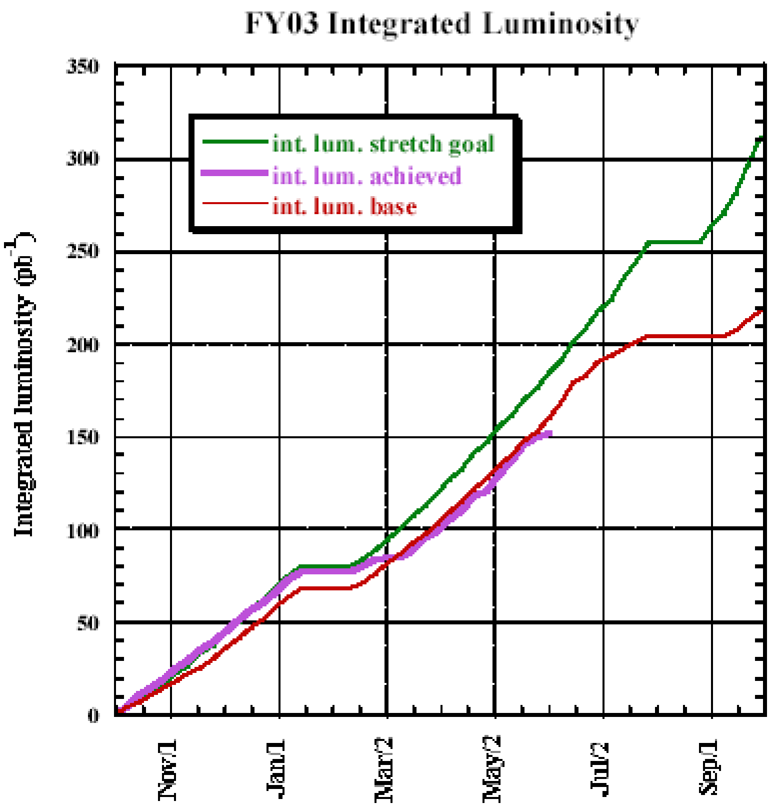
Higher intensity ⇒ Fundamental physics limitations

- Beam-Beam Effects
- Instabilities
- Beam Halo and Lifetimes

Understanding/Solving these issues requires …

- Stable Tevatron Lattice
- Diagnostics
- Study Time

Integrated Luminosity FY 2003



150 pb^{-1} to each detector

Record integrated luminosity 9.1pb^{-1}/week

Beam-beam Interaction As Major Factor

- *Pbar transfer efficiency strongly depends on N_p, helix separation, orbits, tunes, coupling, chromaticity and beam emittances at injection*
- *Summary of progress with beam-beam since March 2002:*

	Mar'02 *	Oct'02 **	Jan'03 ***
Protons/bunch	*140e9*	*170e9*	*180e9*
Pbar loss at 150 GeV	*20%*	*9%*	*4%*
Pbar loss on ramp	*14%*	*8%*	*12%*
Pbar loss in squeeze	*22%*	*5%*	*3%*
Tev efficiency Inj→low beta	*54%*	*75%*	*75%*
Efficiency AA→low beta	*32%*	*60%*	*62%*

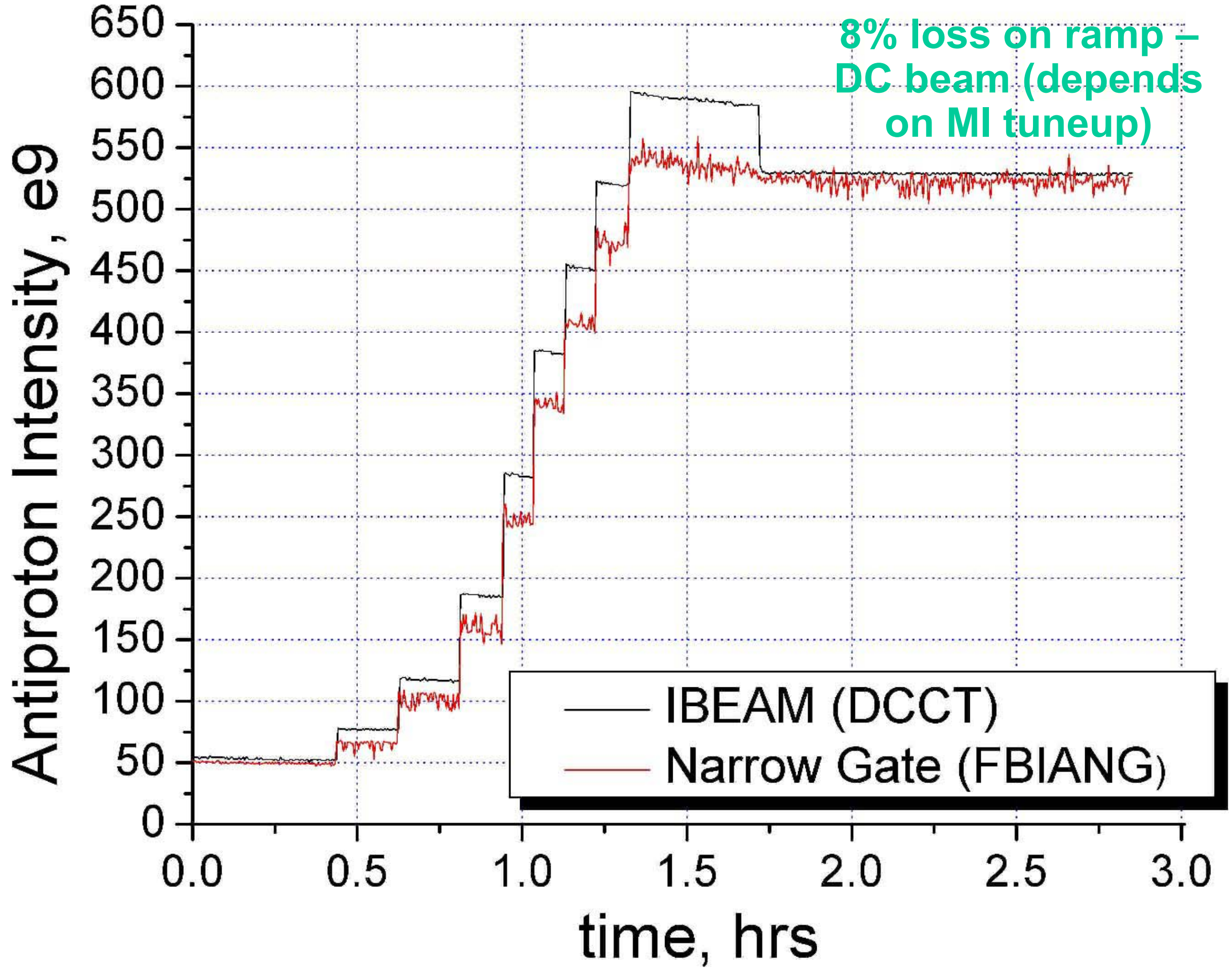
** average in stores #1120-1128*

*** average in stores #1832-1845*

**** average in stores #2114-2153 (9 stores)*

Beam-beam Effects: Pbar Only

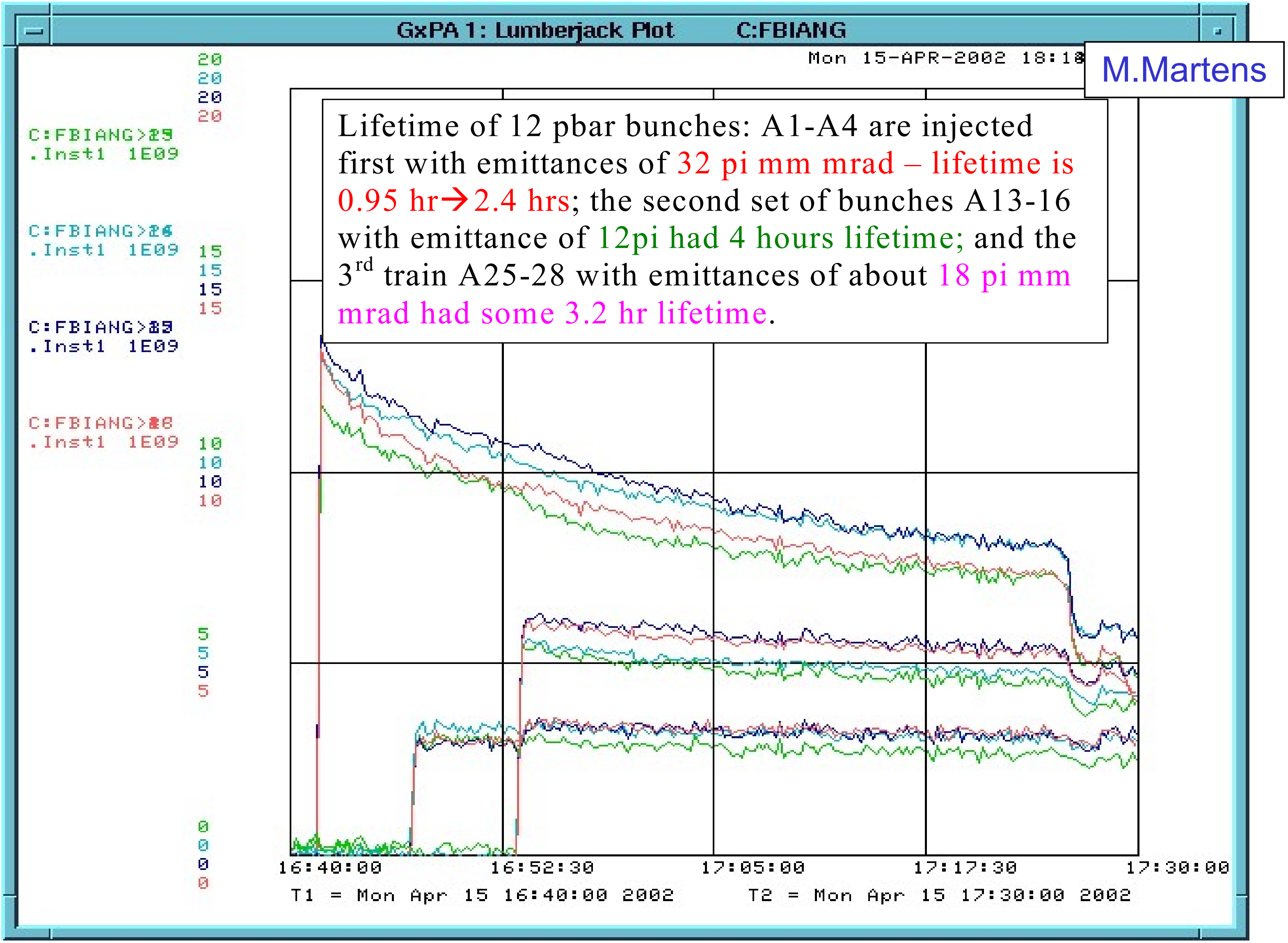
Antiproton Only Store: 1% loss on ramp, τ_{150}=20 hrs, τ_{980}=160 hrs



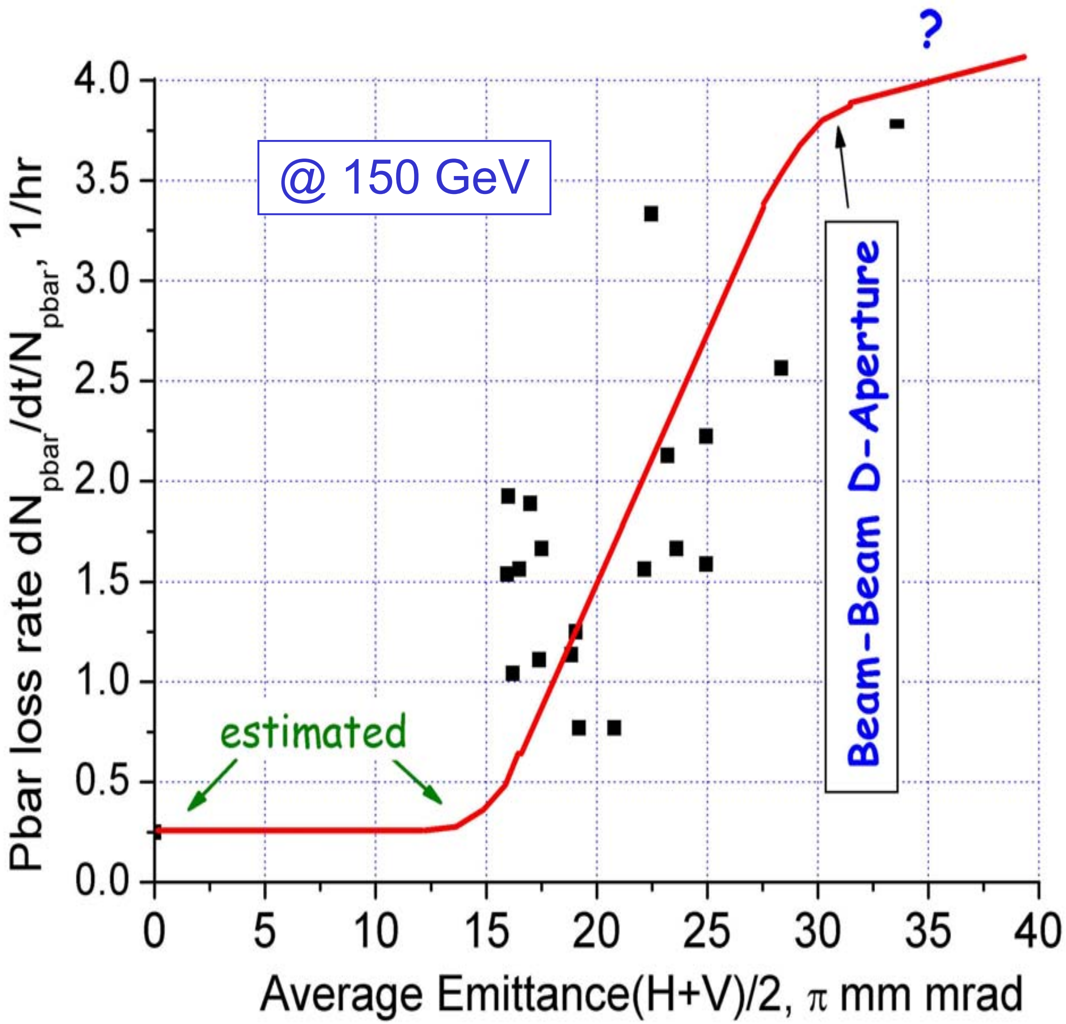
Attacking the Beam-beam Effects

- Smaller emittances from AA ("AA shot lattice")
- Reduced injection errors
  - Beam Line Tuner
- Better control of orbits / tunes / coupling
  - Tunes up the ramp
  - Tune and coupling drift at 150 Gev
  - Orbit smoothing
- Larger injection helix
  - C0 Lambertson replacement
  - New Separator settings

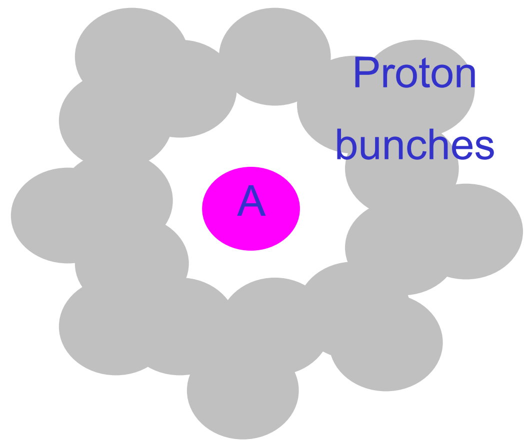
Beam-beam @ Injection Vs Emittance



Antiproton Lifetime at 150 Gev

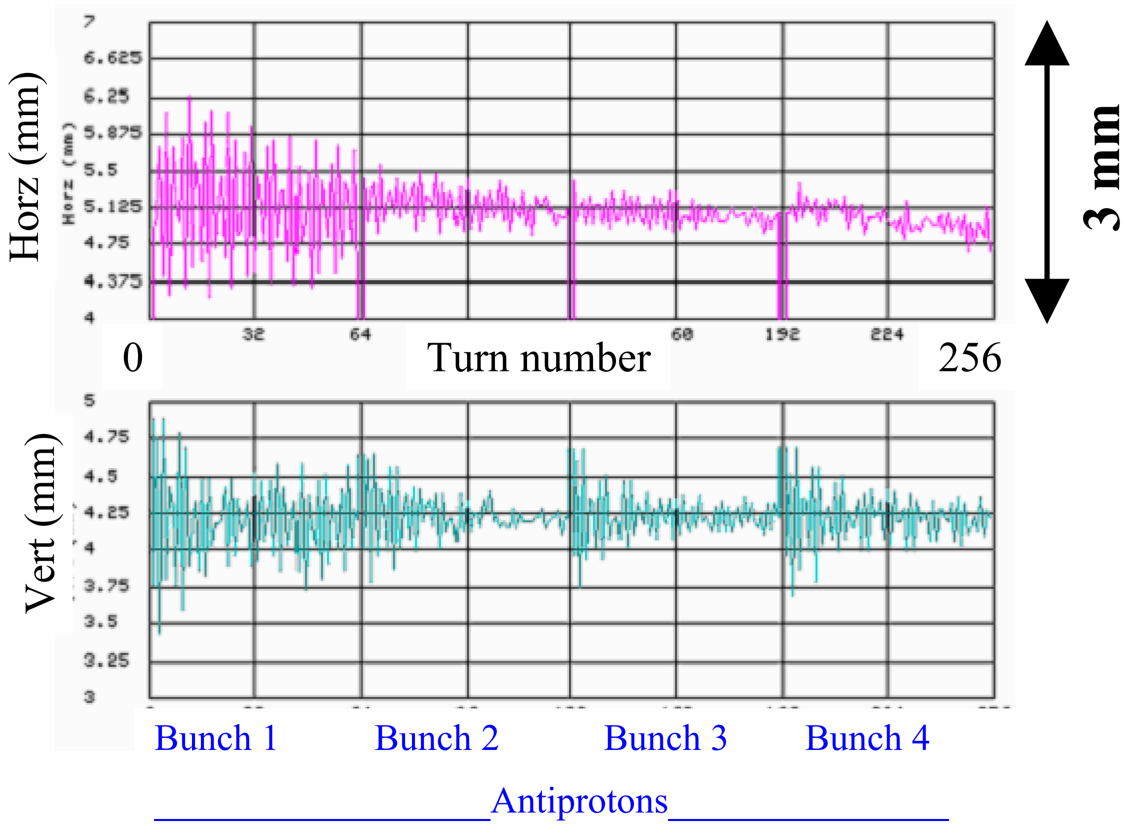


Pbar losses depend strongly on pbar emittances and N_p



Proton Beam as "Soft Donut Collimator"

Injection Oscillations in Tevatron

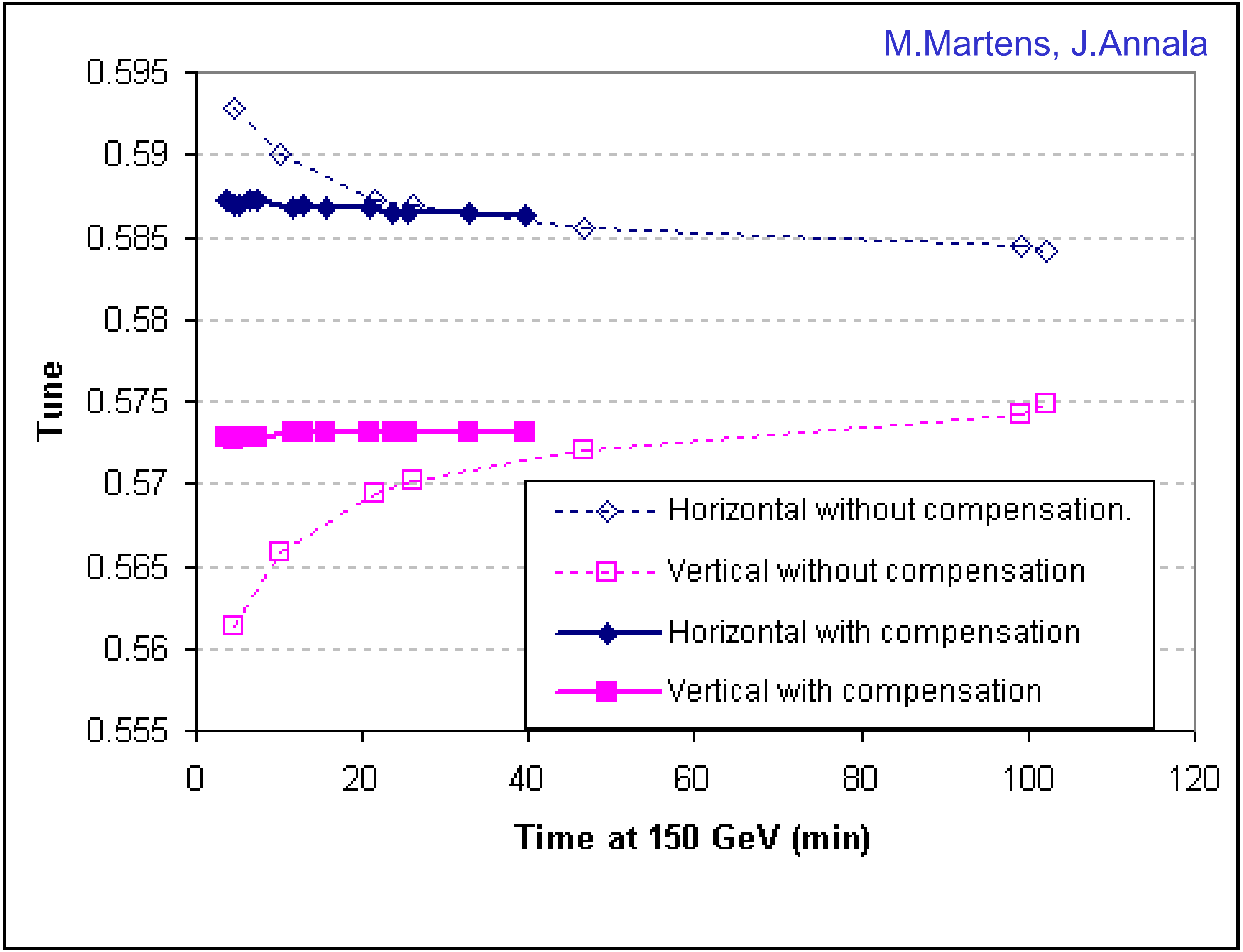


- Turn-by-turn position monitor, (and bunch-by-bunch for pbar)
- Use to tune up injection closure
- 1 mm corresponds to roughly 3-4π emittance blowup
- Improved Pbar emittance blowup by ~3-5π

Tune/coupling/chromaticity/orbits

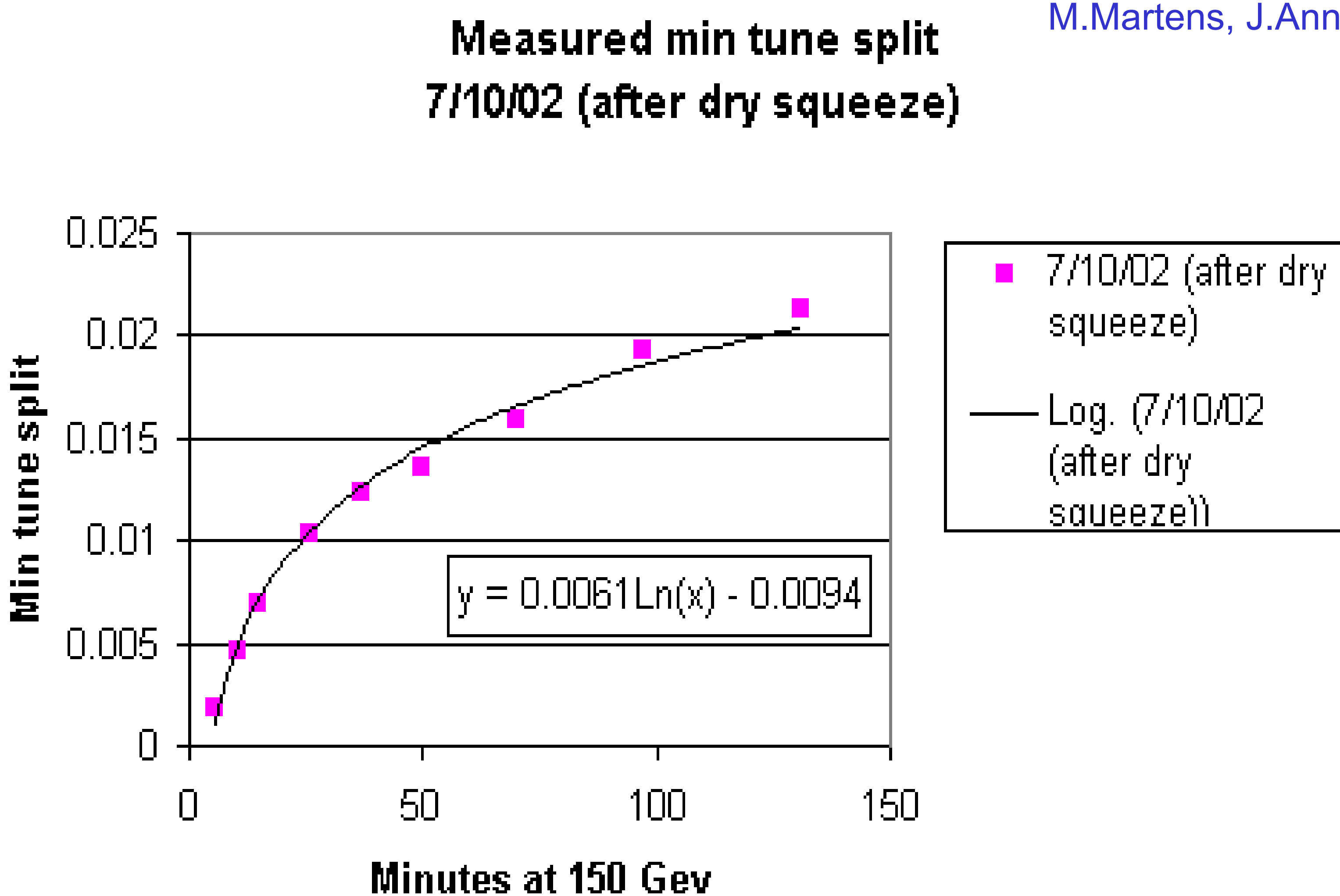
- Tune up is essential for consistent operations …
  - Much effort during "Studies Periods" is actually maintenance (orbit smoothing and tune/coupling/chromaticity adjustments)
- … and for understanding more complicated physics
  - Beam-beam effects, instabilities and dampers, beam lifetimes, beam halo rates, etc. are more difficult to understand when machine parameters drifting.
- Some troubles:
  - Tune/coupling drifts at 150 Gev. (Now compensated.)
  - Tune/coupling snapback on the ramp. (Now compensated.)
  - Chromaticity snapback? (Was measured. Is OK.)
  - Orbit drifts. (Started BPM and smoothing improvements)

Tune Drift @ 150 Gev

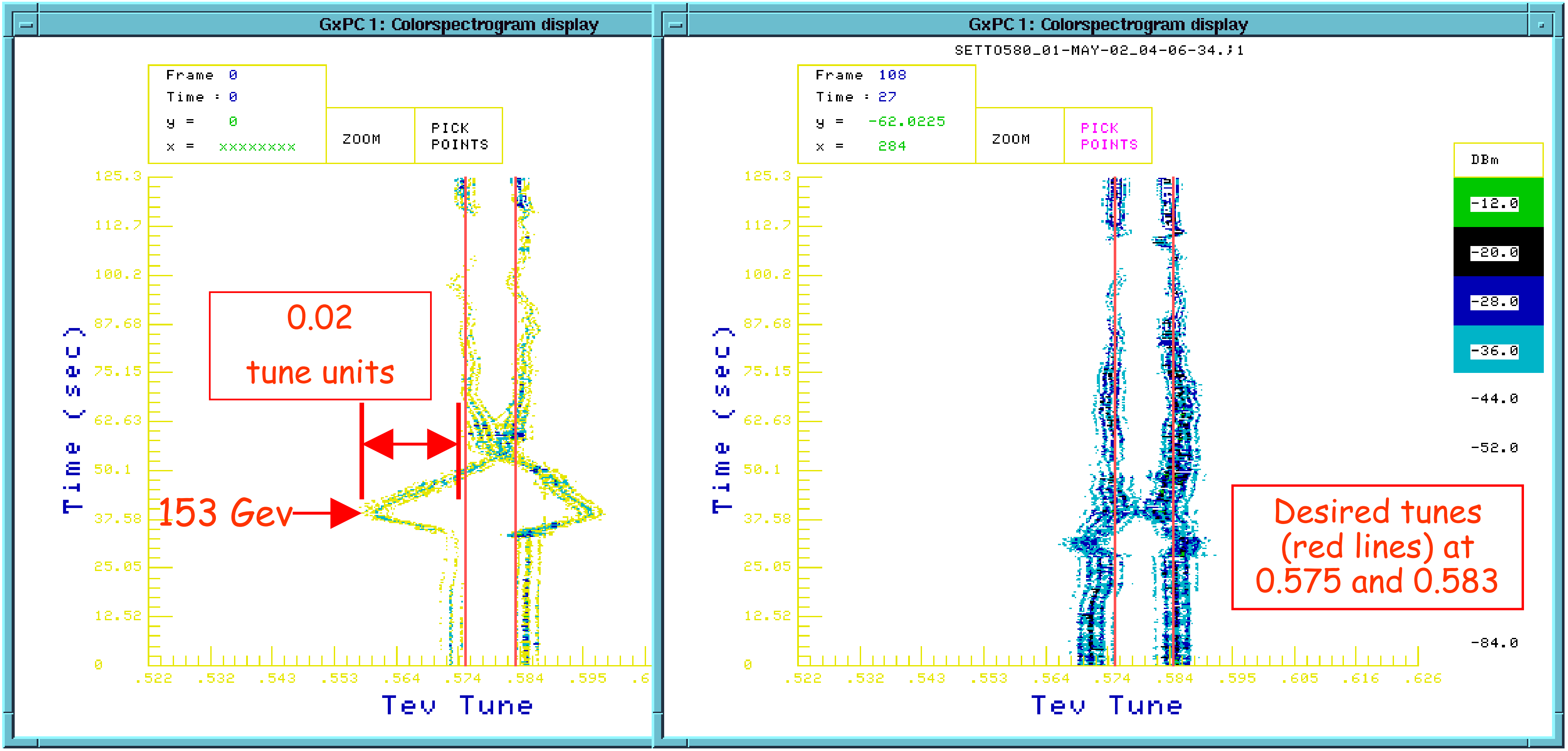


Coupling Drift @ 150 Gev

M.Martens, J.Annala

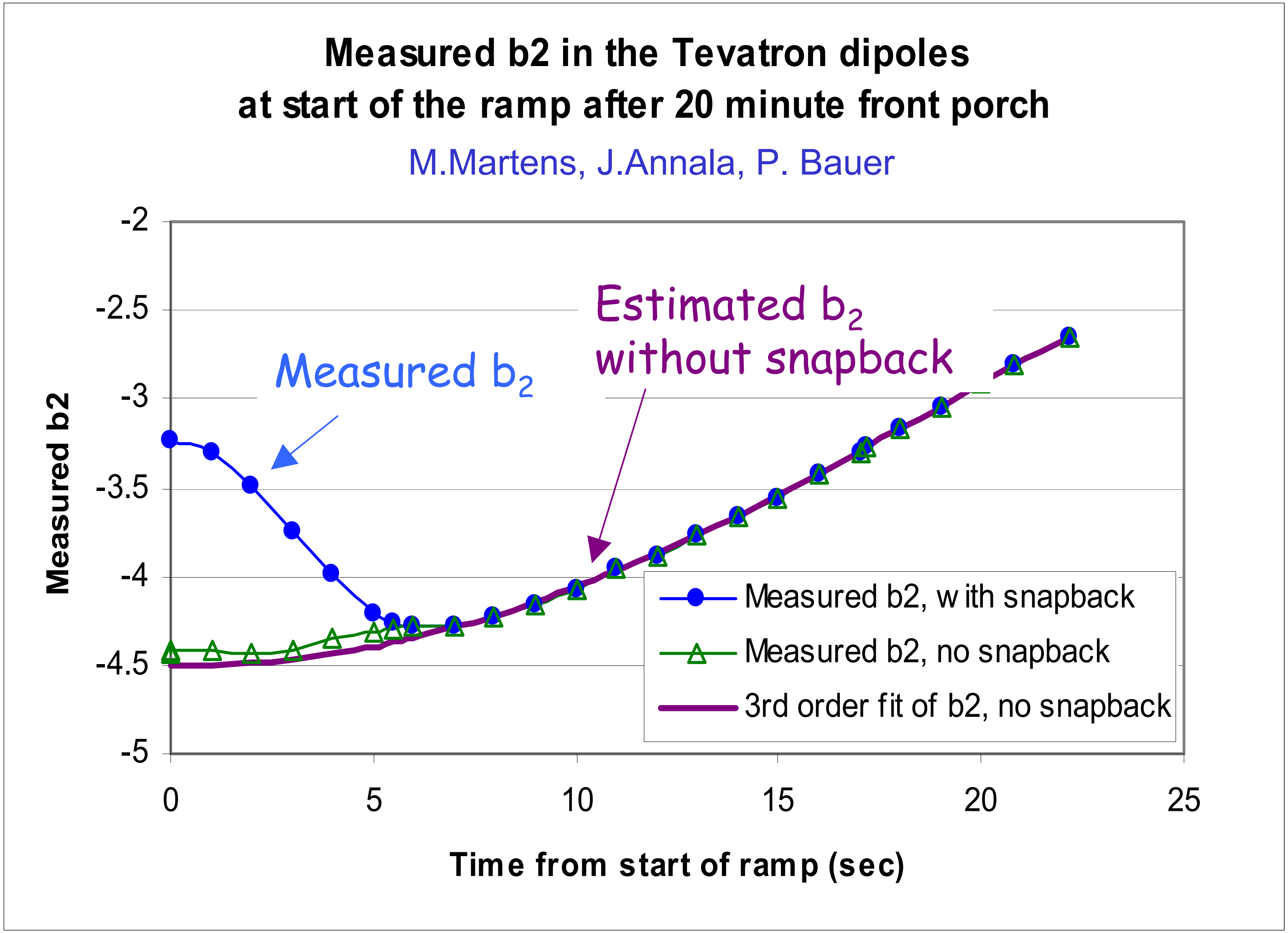


Tune Variations on Ramp/squeeze

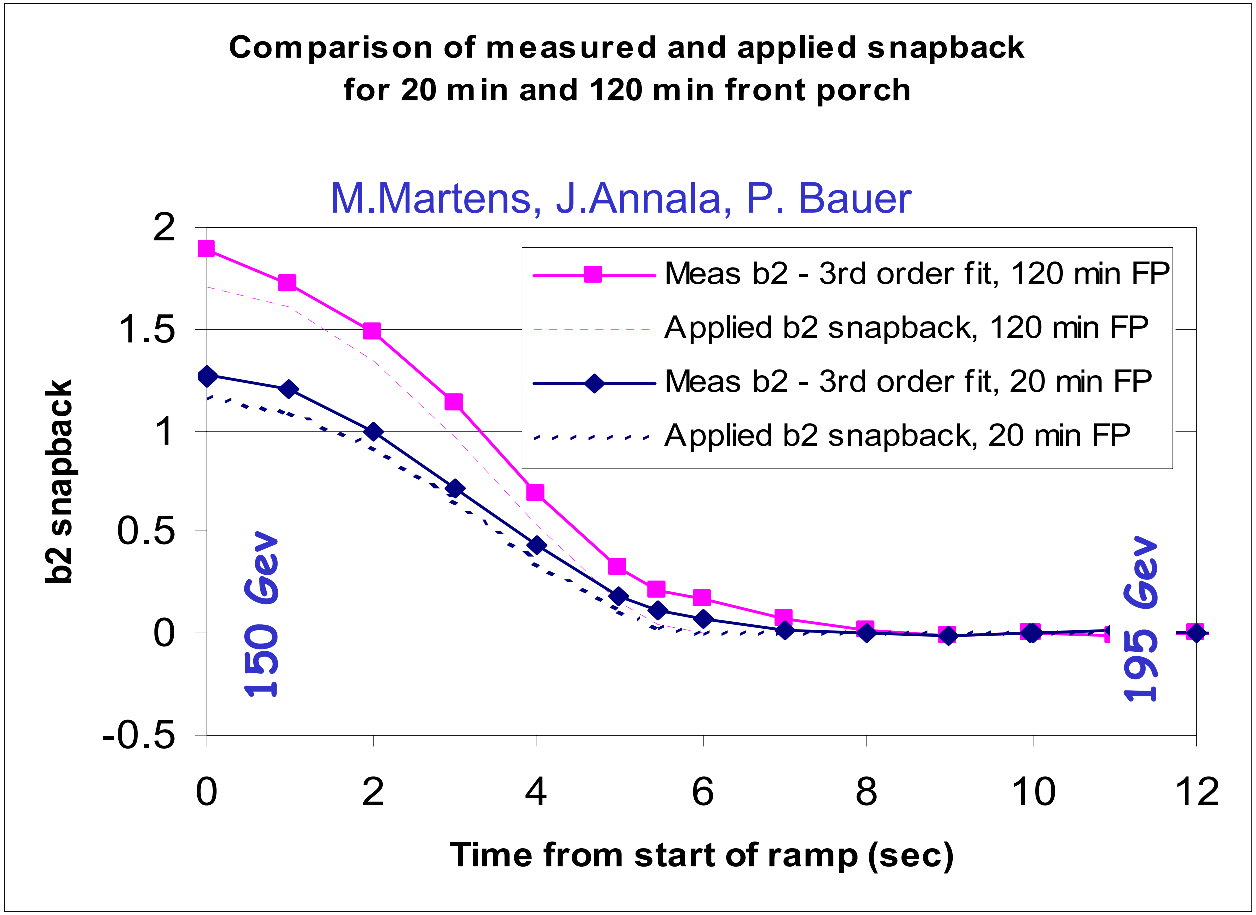


- Near start of ramp (150 → 153 Gev): large tune/coupling excursions
- Tune/coupling changes of (0.02 tune units, 0.02 minimum tune split)
- Variations fixed with <u>additional breakpoint at 153 Gev</u> and <u>tune/coupling snapback correction</u> at start of ramp.

Chromaticity Snapback Measurements

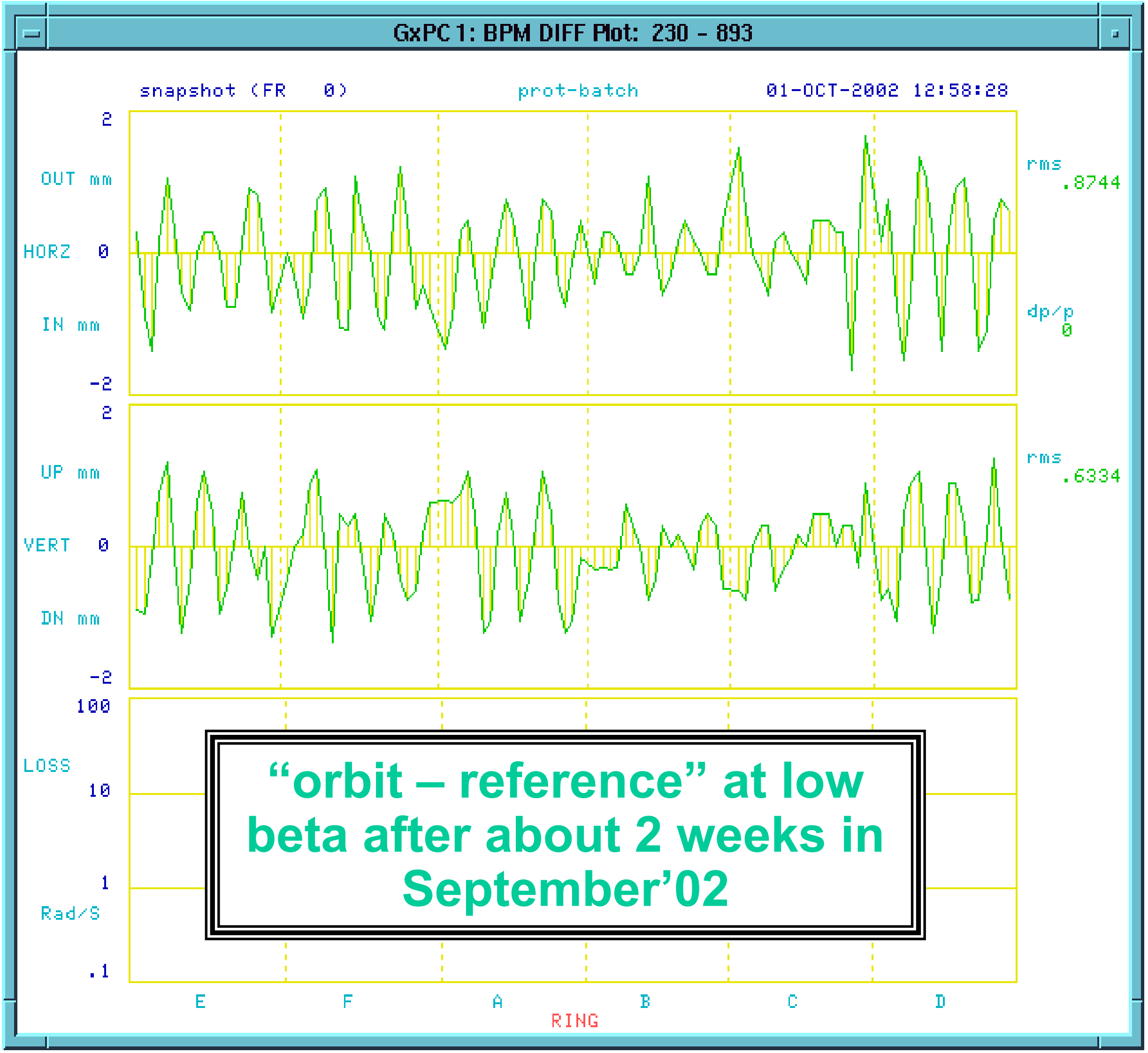


Chromaticity Snapback Compensation



b_2 snapback is correctly compensated (for shot setup conditions.)

Orbit Drifts



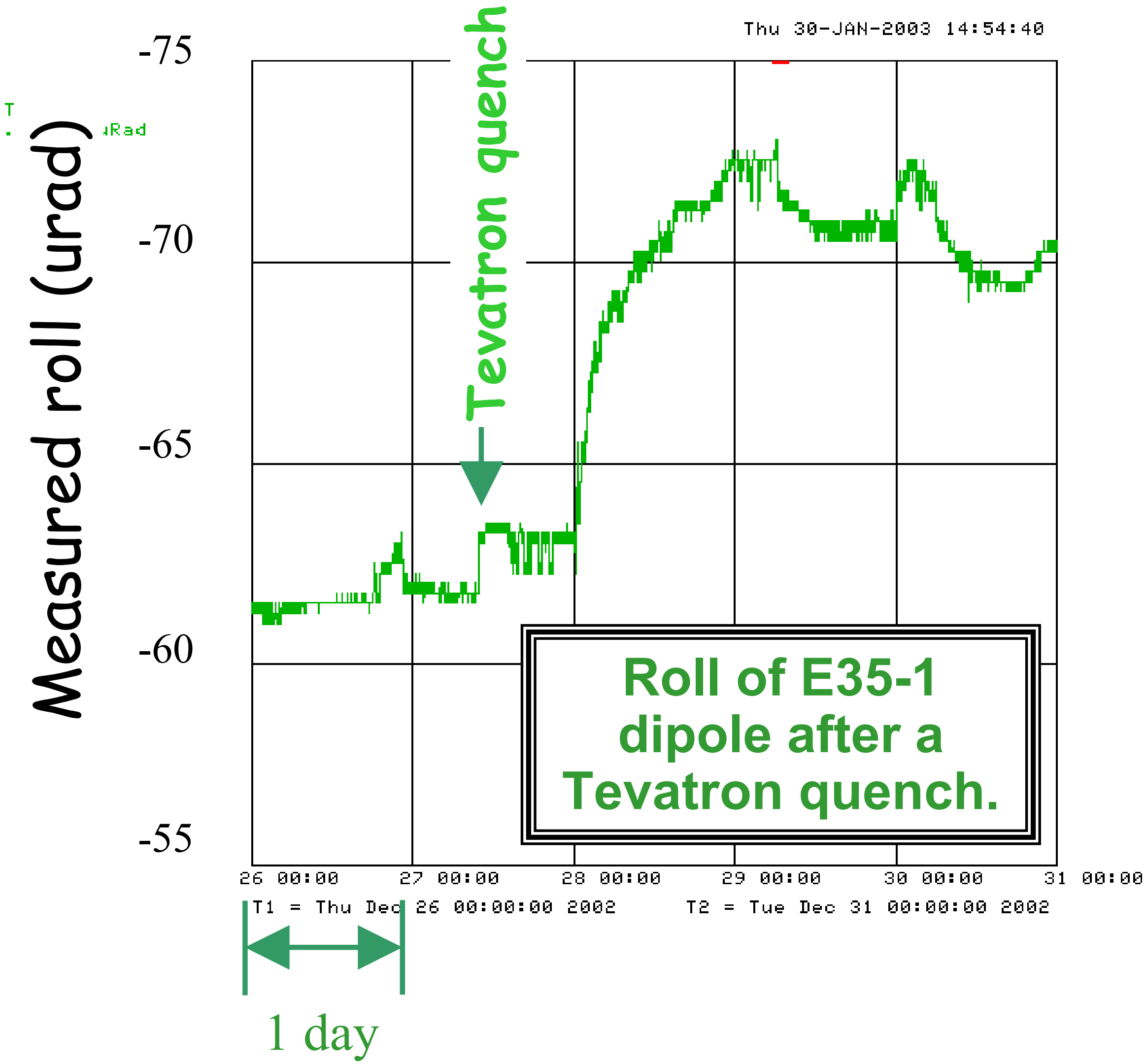
Tunes, coupling, ξ vary with closed orbits distortions

"Rule of thumb" -- keep orbit drifts under 0.5 mm rms from "silver orbit"

Orbit drifts of that scale occur in 1-2 weeks (see picture)

Requires routine orbit smoothing at 150 Gev, ramp, flat-top, squeeze, and low-beta.

Motion of Tevatron Dipole



Newly added a tiltmeter to a Tevatron dipole.

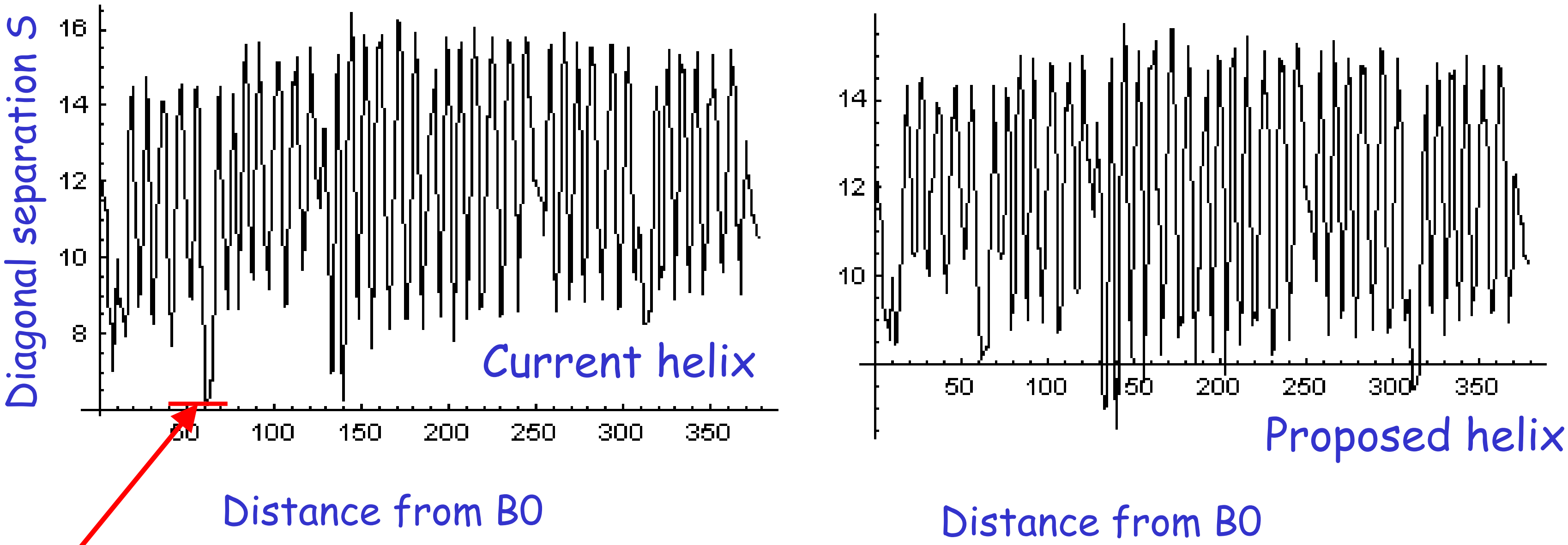
Observed 10 urad roll after a quench

Still watching!!

Larger rolls on other dipoles?

Long term drifts?

Helix Improvement



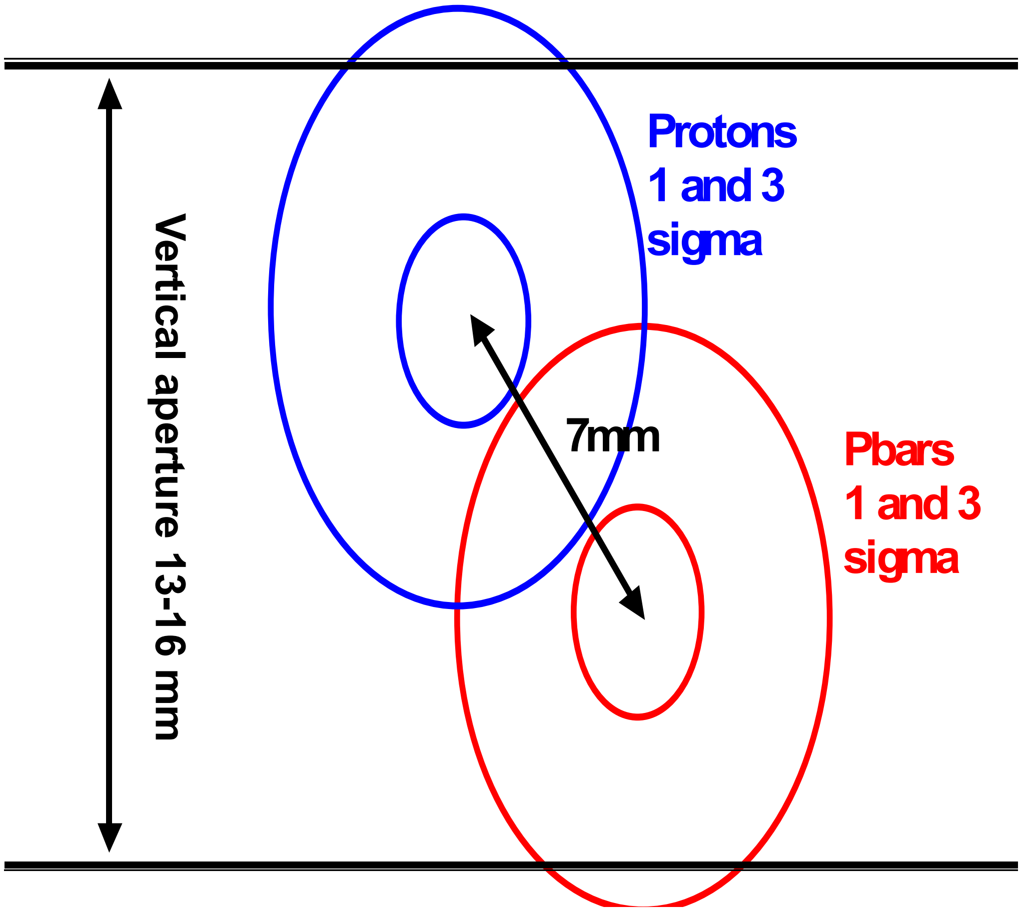
Aperture limitation at C0

$$S = \sqrt{(\Delta x / \sigma_x)^2 + (\Delta y / \sigma_y)^2}$$

Increasing proton/pbar helix separation

- Replace C0 Lambertson with MI magnets
- Increase vertical aperture at C0 from ~15mm -> 40 mm (but only ~30% larger helix due to other aperture limitations.)
- Modify helix to increase min separation, S_{min}, from 5.5 to 6.6

C0 Lambertson Replacement



Proton and pbar beam position and sizes on the helix at the location of C0 Lambertson

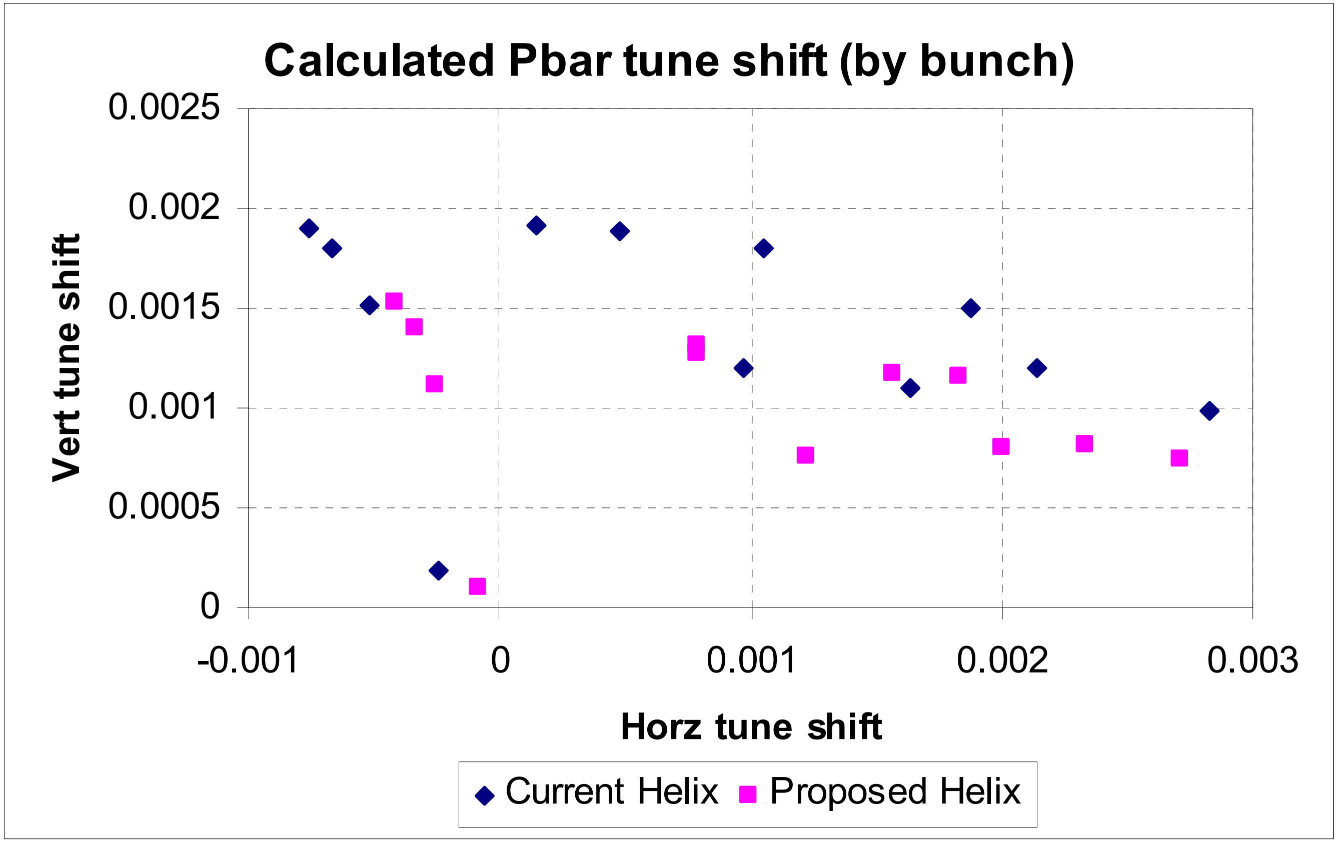
Pbar lifetime depends on emittances and helix size.

C0 Lambertson is severest aperture restriction. (See picture)

Design injection helix modified and optimized to fit tight C0 aperture ("new-new helix")

(Jan 2003)
Replace C0 Lambertsons
Gain 25 mm vertically

Beam-beam Tune Shift Reduction

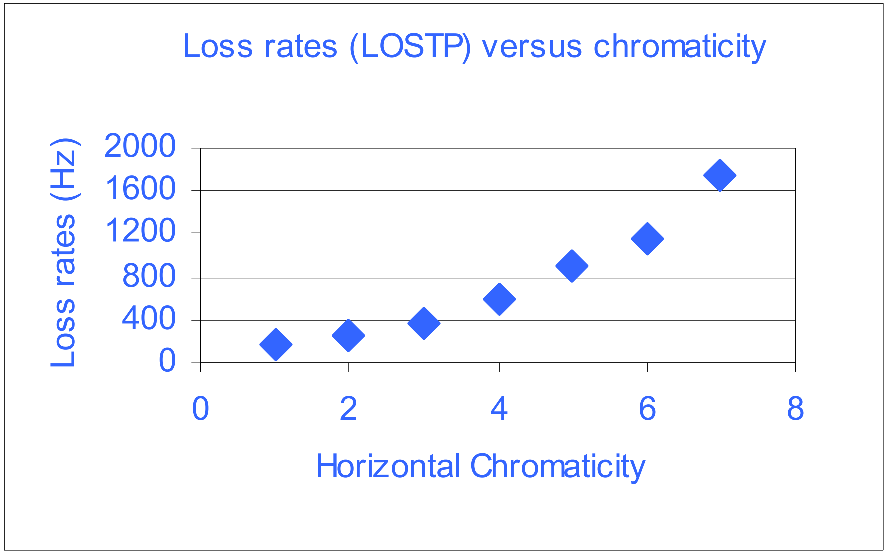


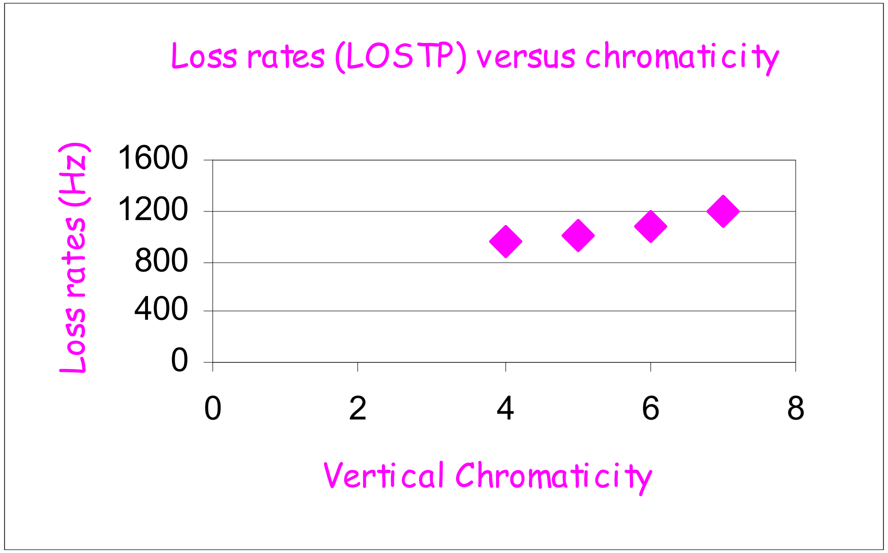
Proposed injection helix (with larger C0 aperture) will reduce small amplitude tune shift of pbars

Proton Lifetime Issues at 150 Gev

- Poor proton lifetime on helix ~ 2 hr
  - depends on chromaticity
  - Instability prevents lower chromaticity (now 8)
  - Orbits/size of helix affect lifetime
  - Tunes/coupling are a factor

Lifetime and Chromaticity at 150 Gev



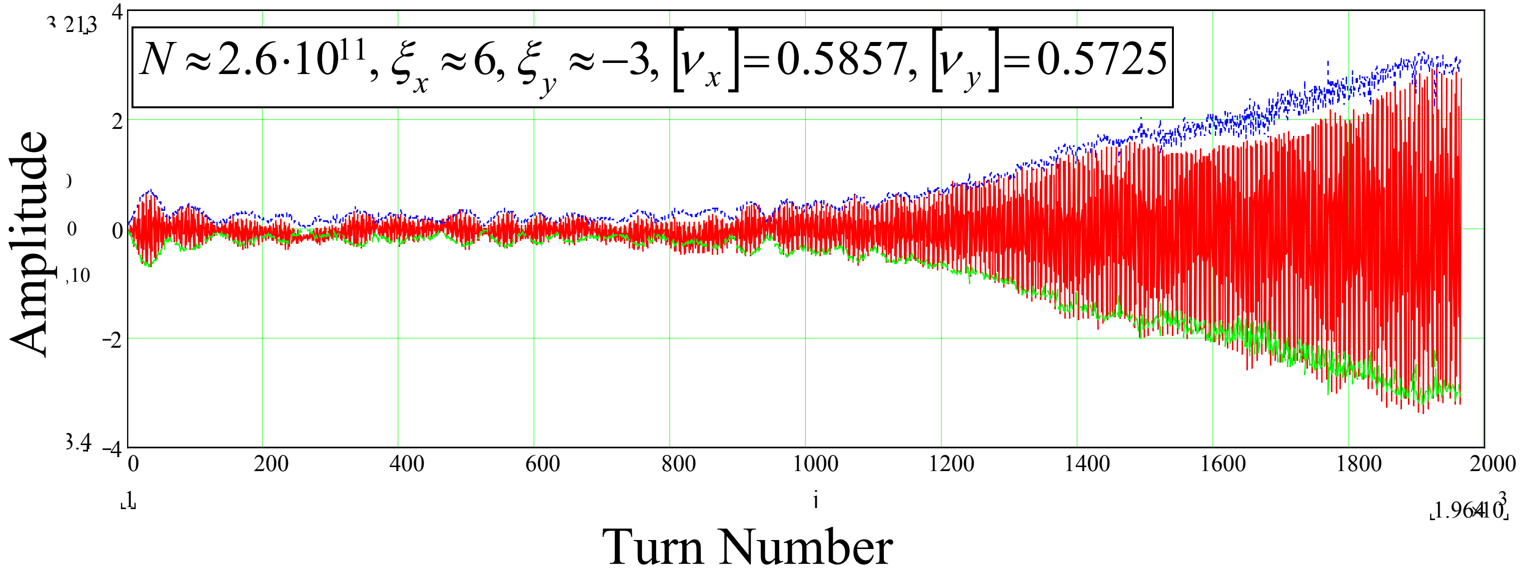


Measured loss rates as function of chromaticity (with protons on the pbar helix)

- Lower chromaticity is better for lifetime
- Instabilities appear ξ < 3-4
- Run with $\xi_H = 8$, $\xi_V=8$ to avoid instabilities
- Dampers allow us to lower chromaticity and improve lifetime

Unstable Head-tail Motion

Developing head-tail instability with <u>monopole</u> configuration
Beam is unstable for $\xi_x \approx 6$, $\xi_y \approx -3$
Longitudinal and transverse dampers OFF
N_p= 260E9

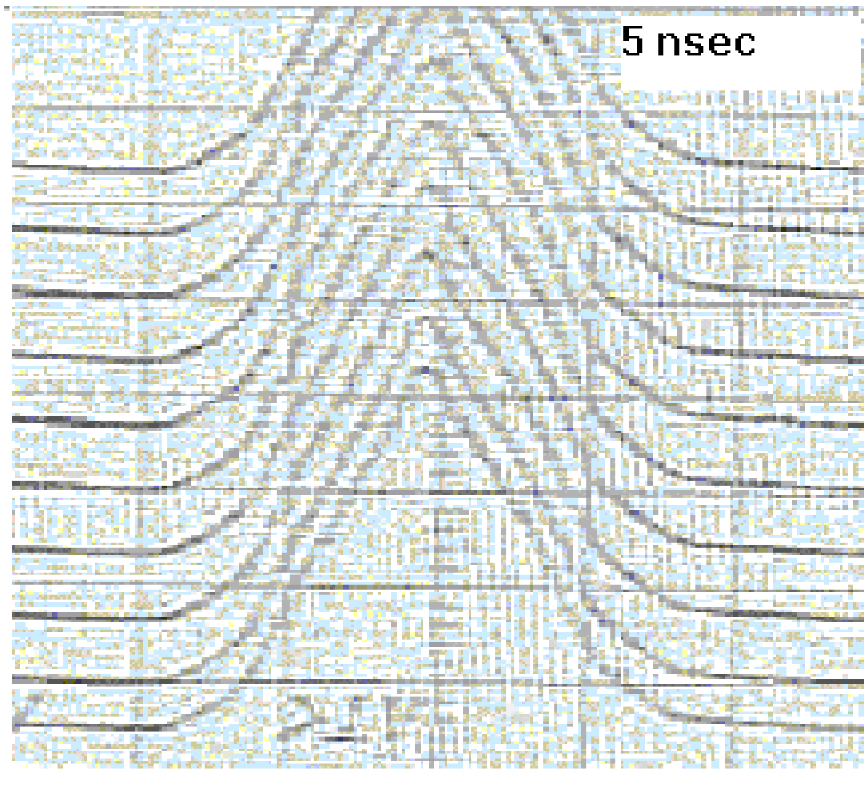


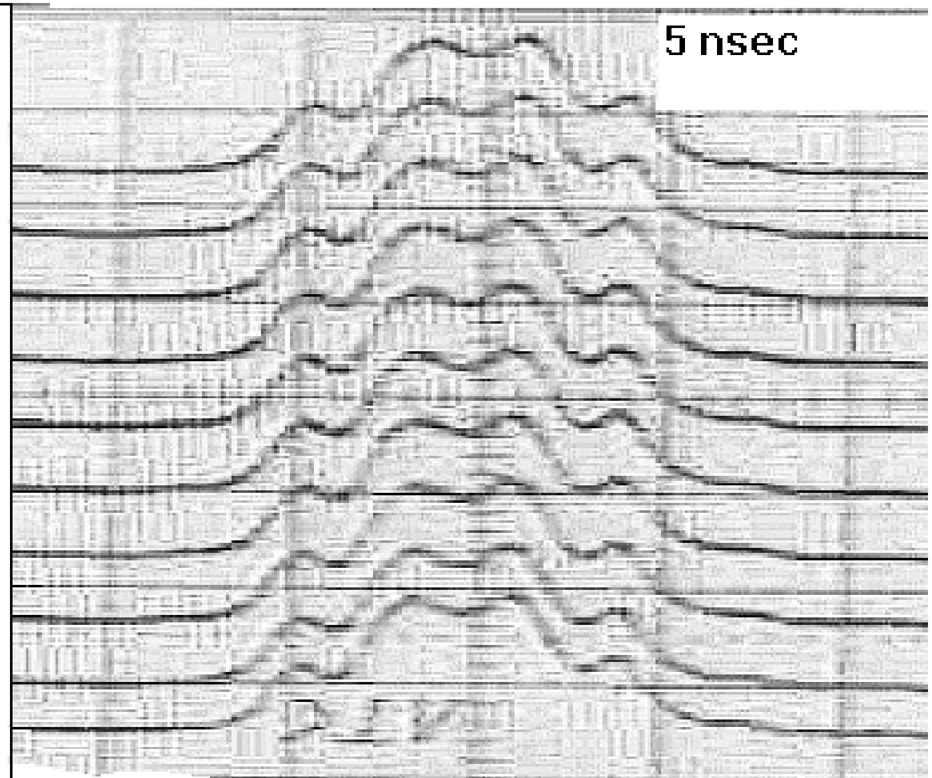
Transverse Instability

- Beam remnants point to coherent betatron mode with ***l=2***

$$N_{ppb} = 2.6 \cdot 10^{11} \left(init.\ beam \right) \quad \Rightarrow \quad N_{ppb} = 1.03 \cdot 10^{11} \left(remain.\ beam \right)$$

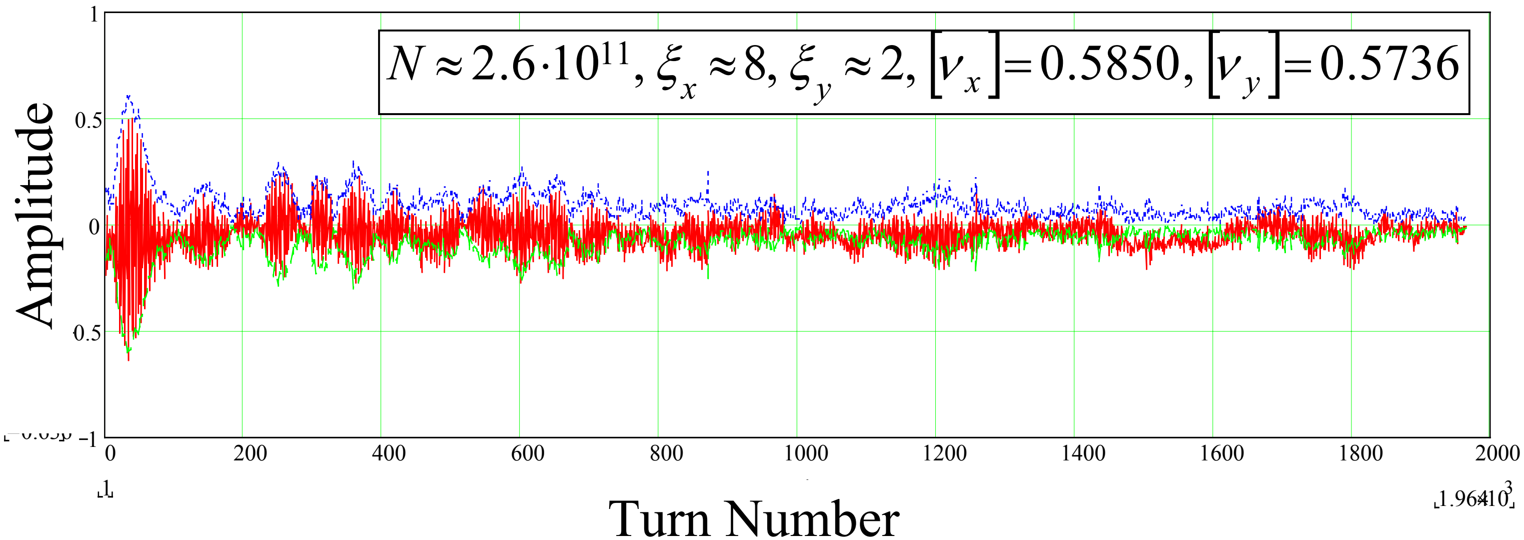
P.Ivanov, A.Burov



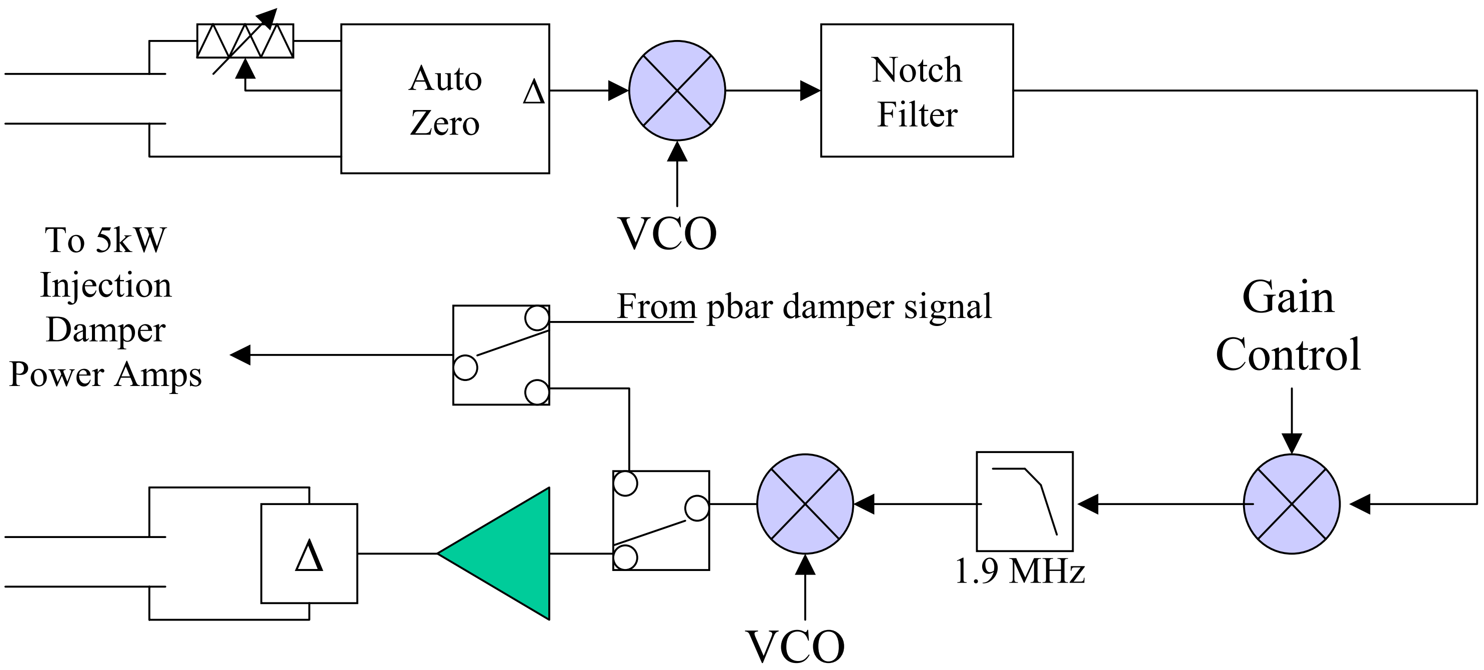


Unstable Head-tail Motion

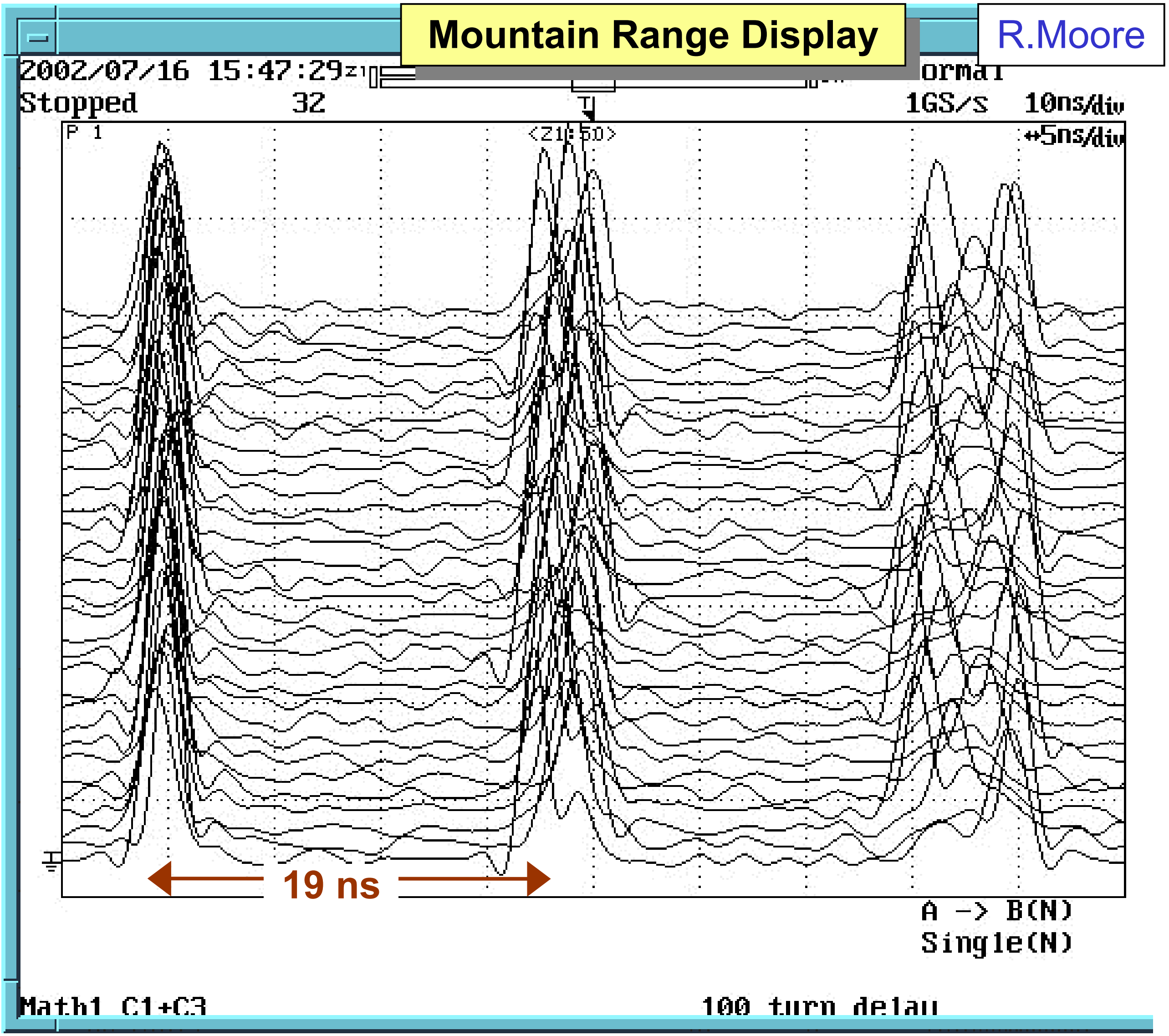
Observed transverse oscillation for <u>stable</u> conditions
Beam is stable for $\xi_x \approx 8$, $\xi_y \approx 8$
Longitudinal and transverse dampers OFF
N_p= 260E9



TeV Transverse Damper

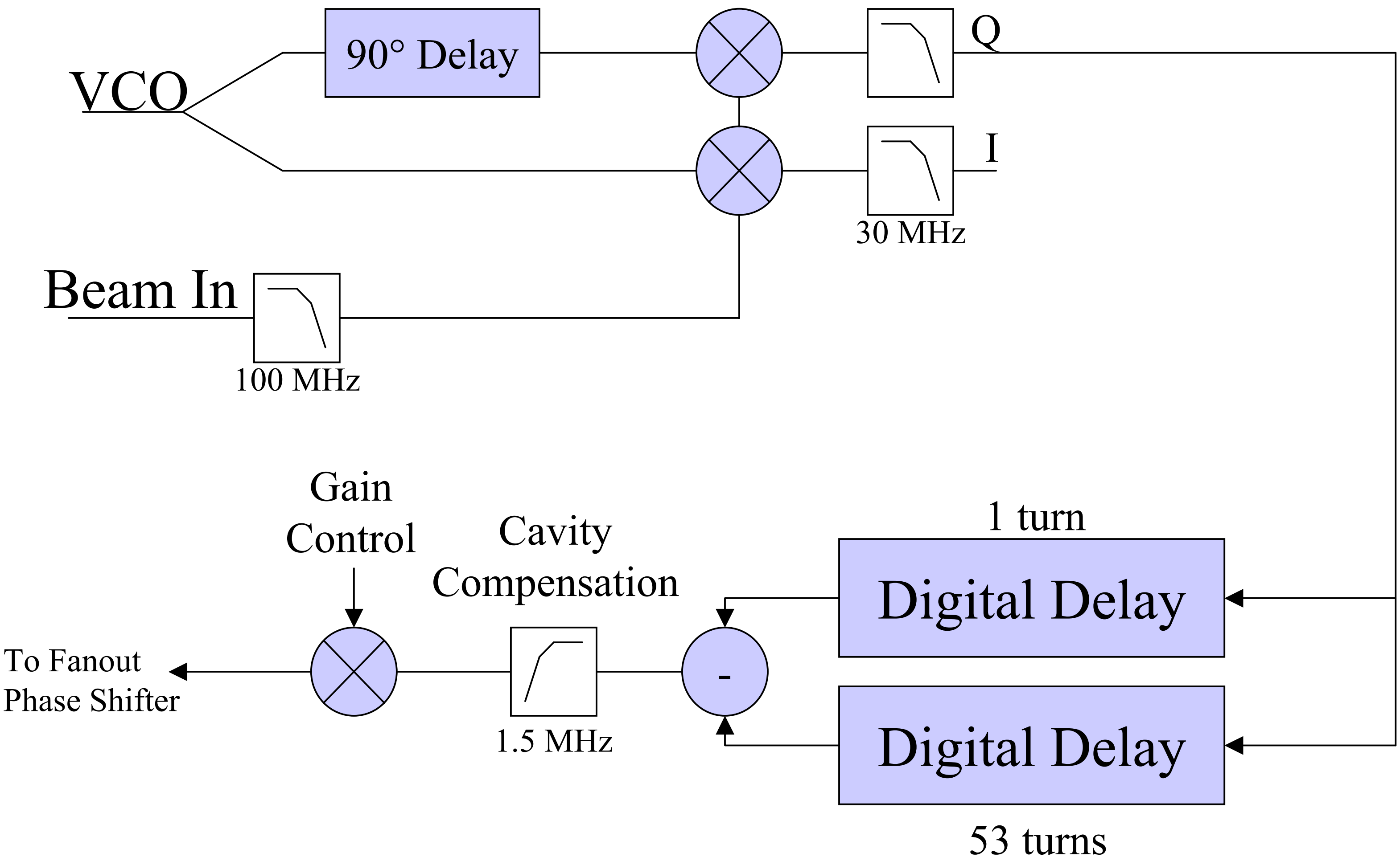


Longitudinal Impedance – "Dancing Bunches"

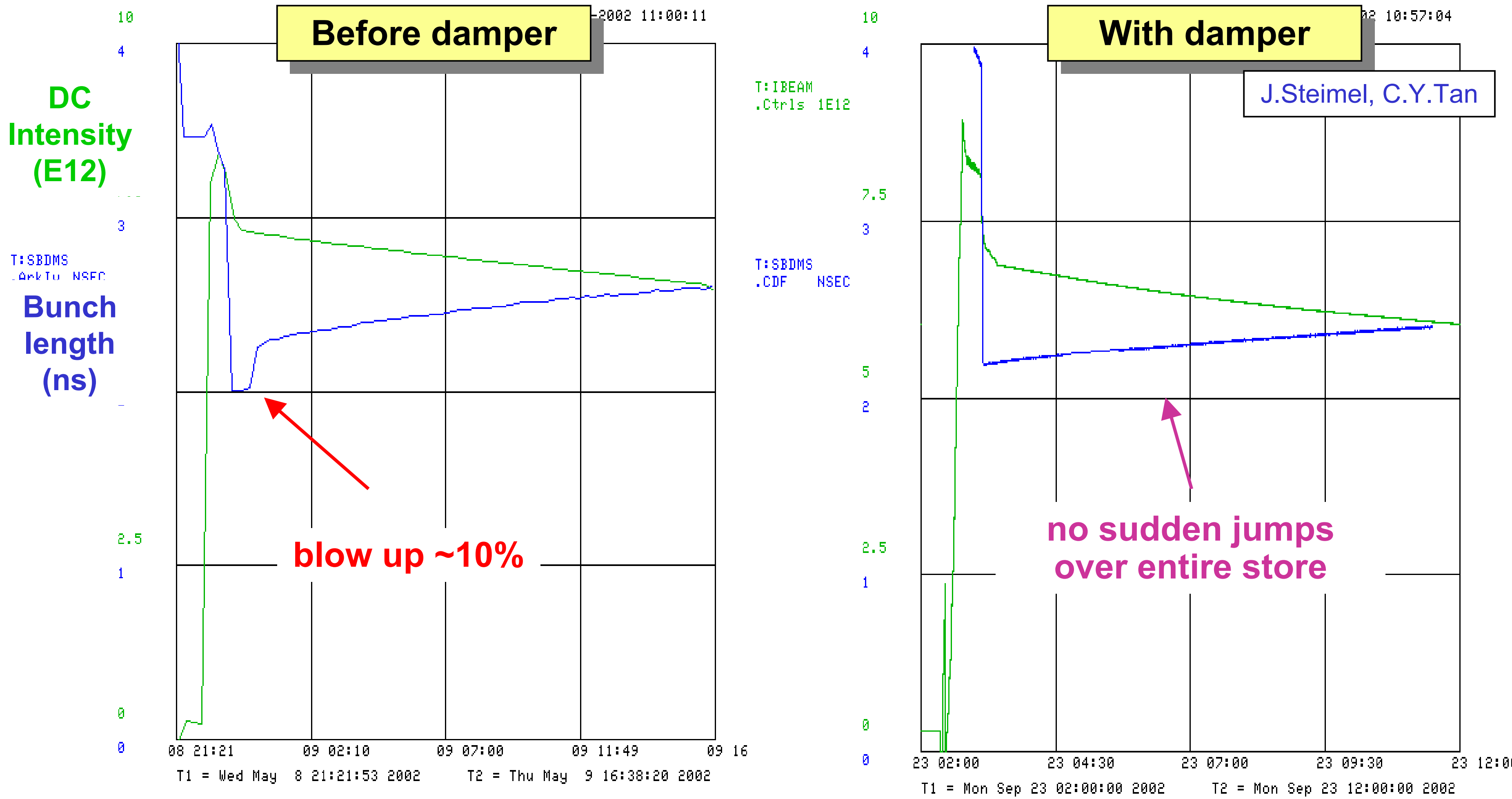


- Beam in 30 buckets
- 100 Tevatron turns (~2 ms) between traces
- Synch freq ~ 85 Hz
- Oscillation amplitude depends on bunch, changes slowly with time (minutes at 150 GeV, seconds at 980 GeV)
- Model needs inductive impedance Z/n ≈ 2 Ohm interplaying with cavity impedance
- Coalesced bunches have dancing bumps

TeV Longitudinal Damper Block

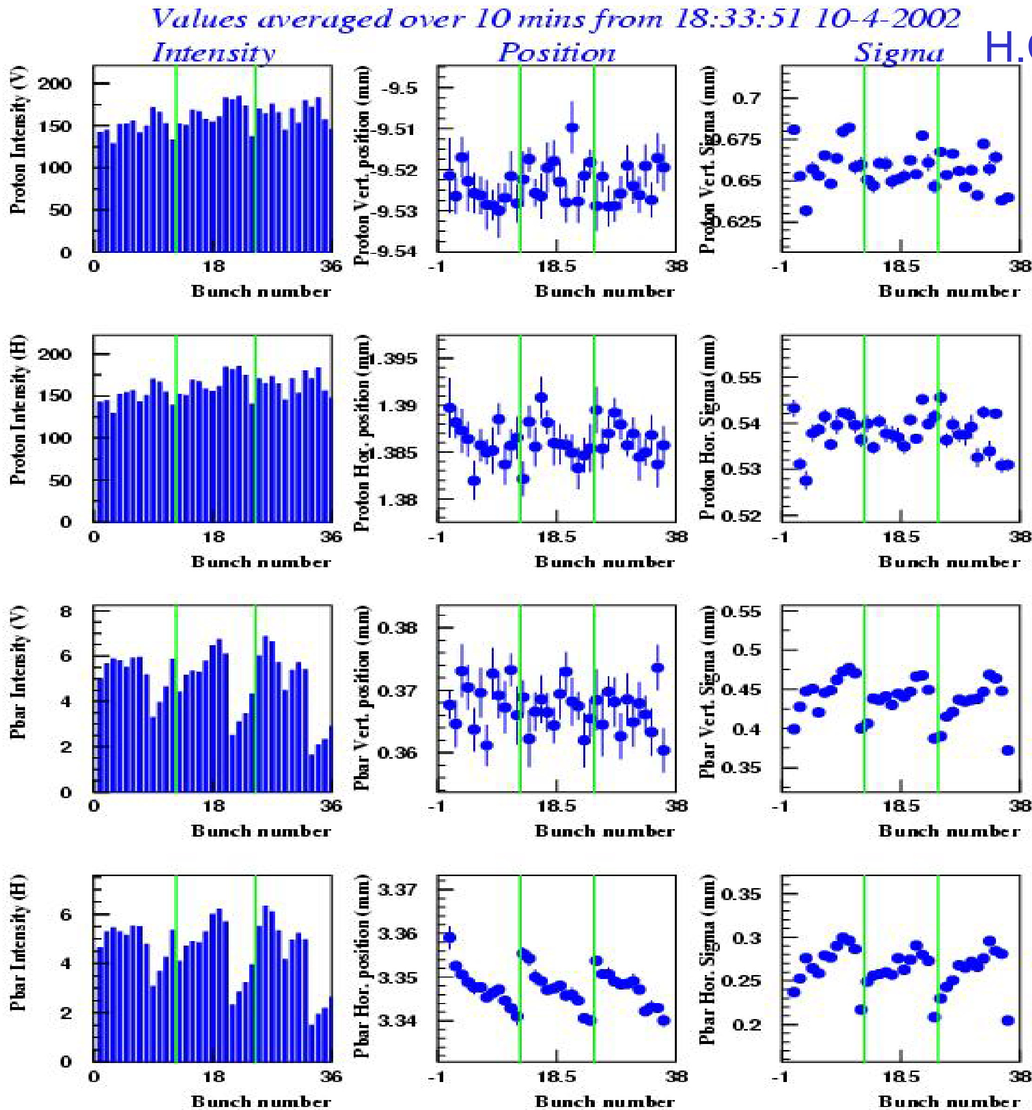


Bunch Length Blowup During Stores



- Intensity-dependent, leads to significant CDF background rise
- Usually only one or a few bunches would suffer
- Problem solved by <u>bunch-by-bunch longitudinal damper</u>

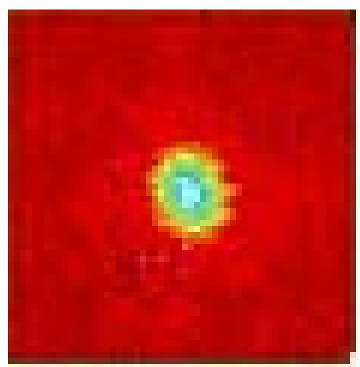
Diagnostics Progress: SyncLite Monitor



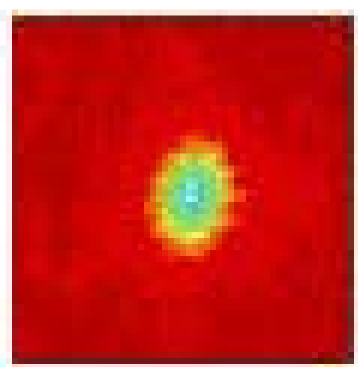
H.Cheung

- Works >800 GeV
- Significant progress since March'02
- Reports rms, mean, N, tilt bunch-by-bunch for both protons and pbars
- Invaluable instrument

Bunch #1

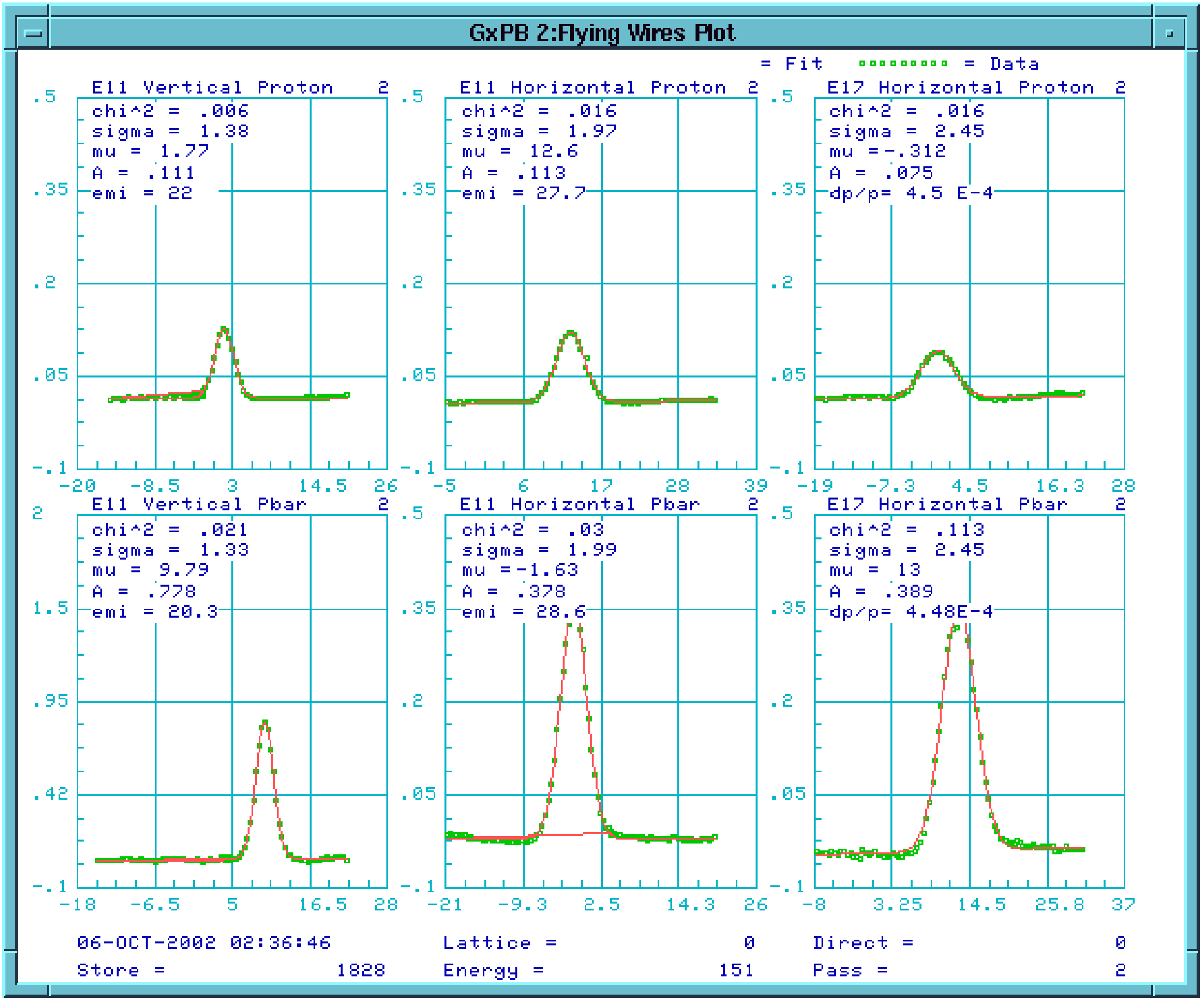


Bunch #8



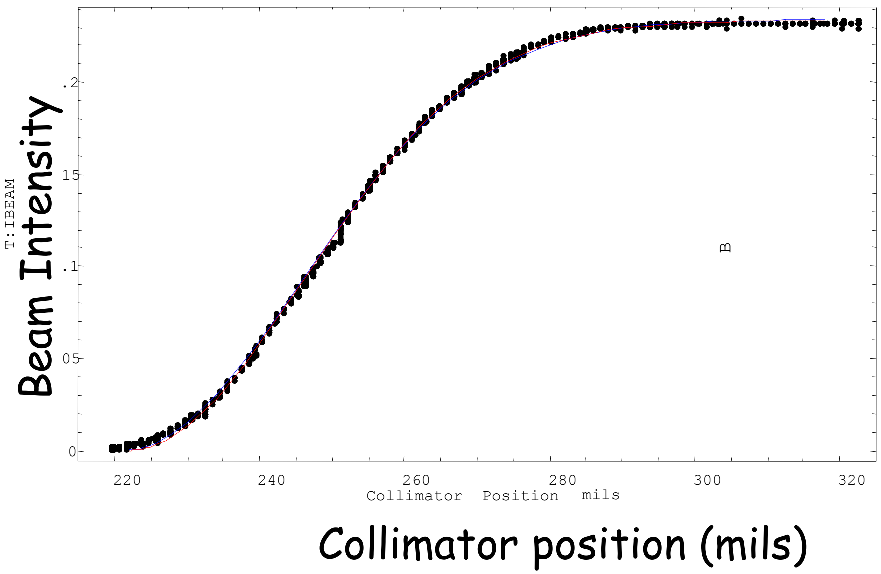
Diagnostics: Flying Wires

#1828, injection



- Proton channels tuned up in March
- Still some (15% ?) calibration needed
- Pbar channels data are subject of correction
- “Jumping” emittances
- (improper dP/P?)
- Recalibration of both p and pbar channels is due
- Need raw data

Tev Scraping Studies



Intensity versus collimator position assuming Gaussian beam (1D scraping):

$$N = N_0 \left(1 - e^{-\frac{(x - x_0)^2}{2\sigma^2}}\right)$$

Vertical prot emittance measurement
(95%, normalized)

Use scrapers to measure emittance. Then compare to FW and Sync. Lite

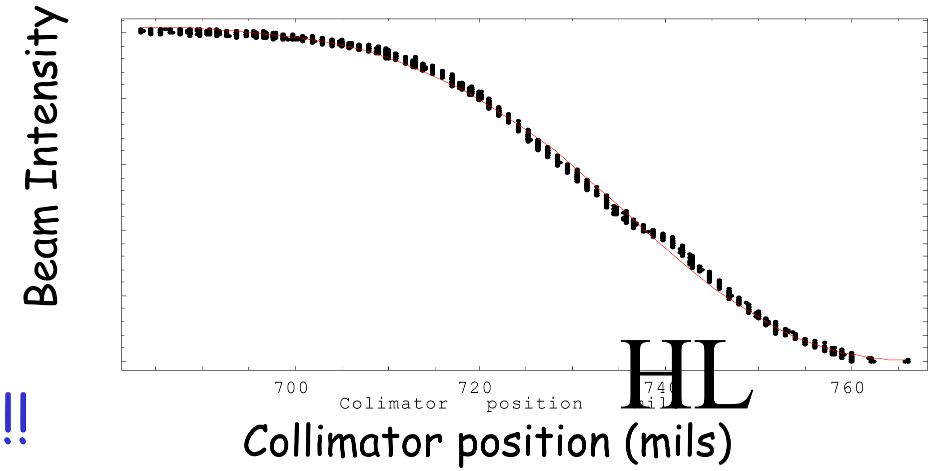
Scraping:	24-27 π
Flying Wire:	30 π
Sync. Lite:	34 π

Need to know β function at monitors!

Tev Scraping Studies

Horizontal proton

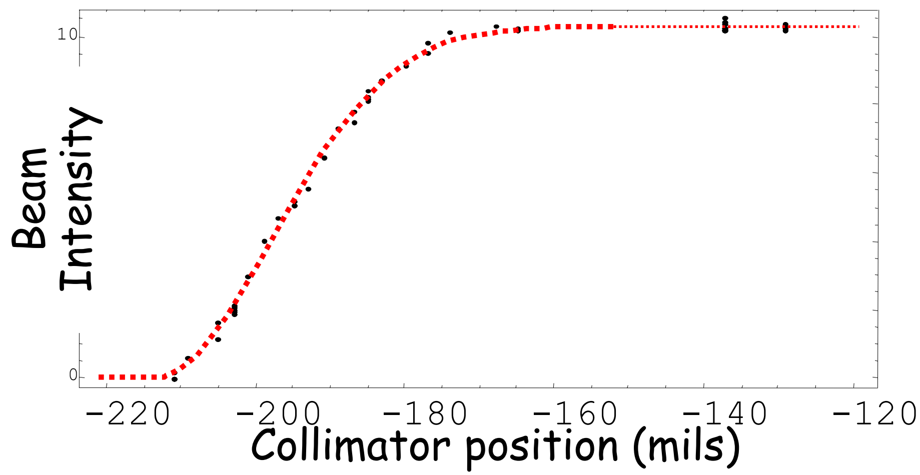
Scraping: 31-33 π
Flying Wire: 22-28 π
Sync. Lite: 34 π



Dispersion is an issue !!!

Vertical pbar

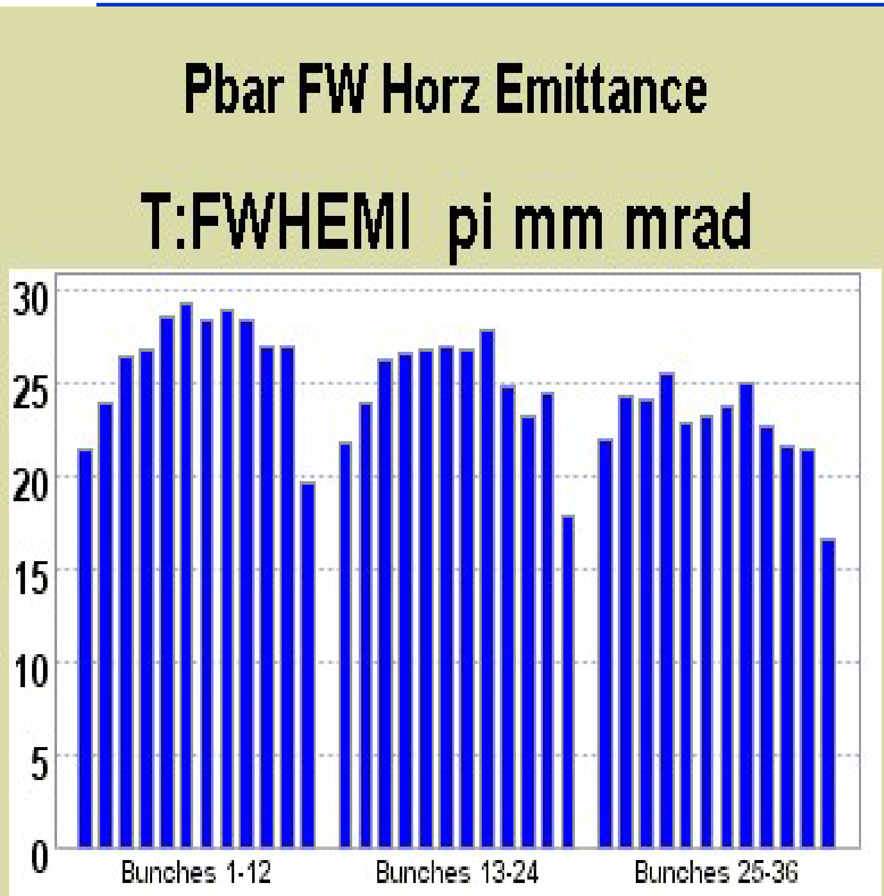
Scraping: 20-24 π
Flying Wire: 42 π
Sync. Lite: 44 π

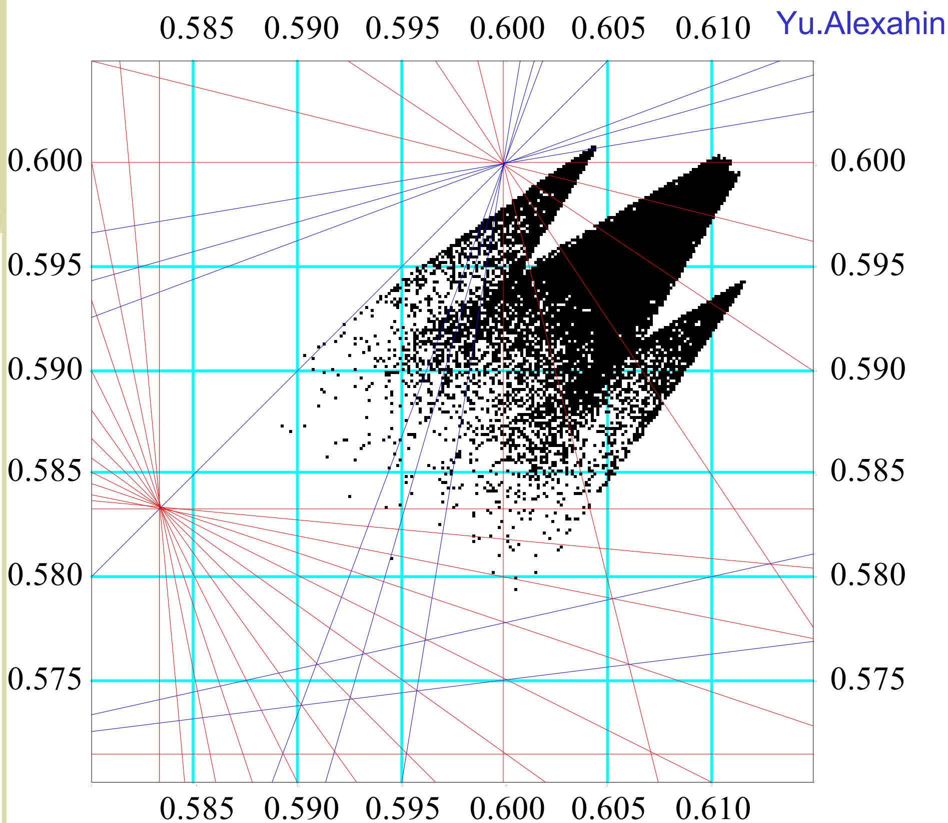


Progress on Tevatron Physics Issues

- Lattice Measurements
- F0 Lambertson major impedance source
- Smart bolts and coupling
- 1st indication of Beam-beam comp. (TEL)
- Dancing bunches analyzed
- New 1.5 GHz Schottky tune detector
- SBD/FBI calibration
- Work on the new helix
- Octupole studies to improve beam stability

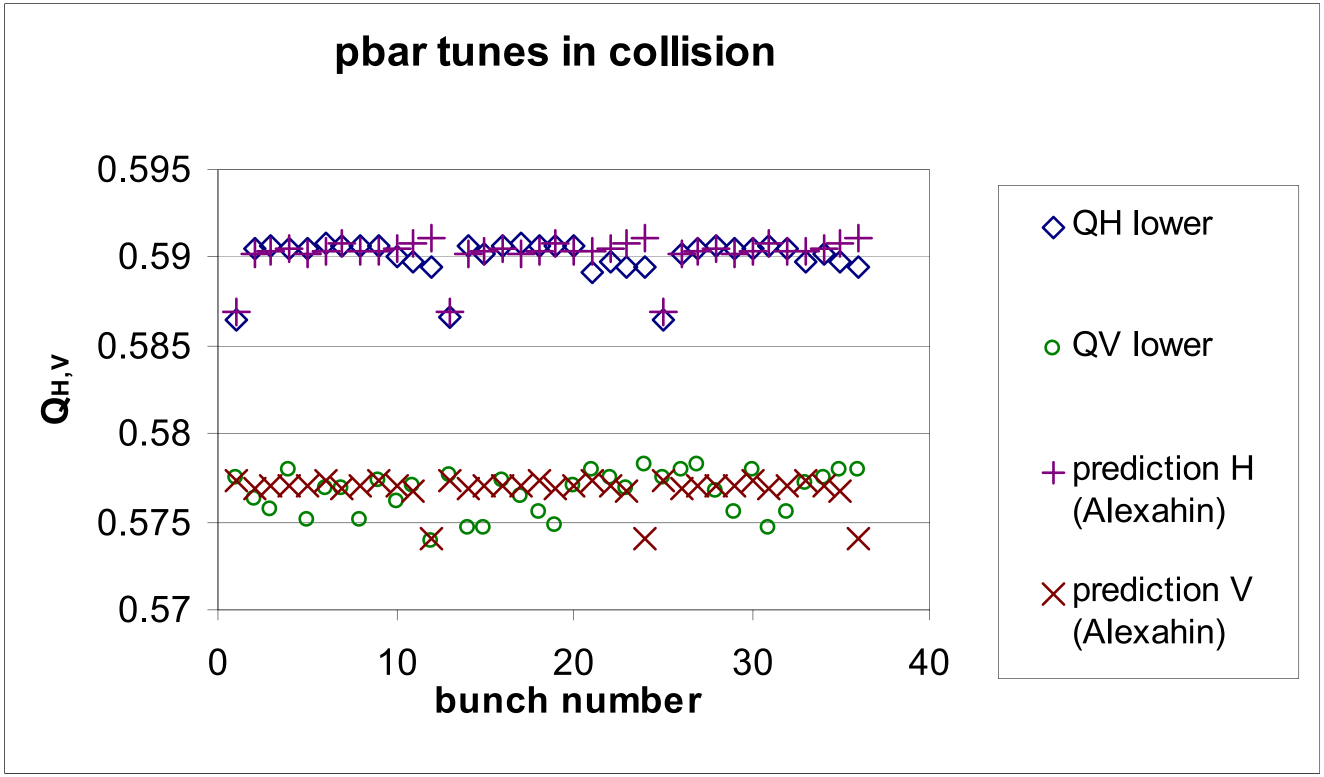
Beam-beam Effects at 980 Gev





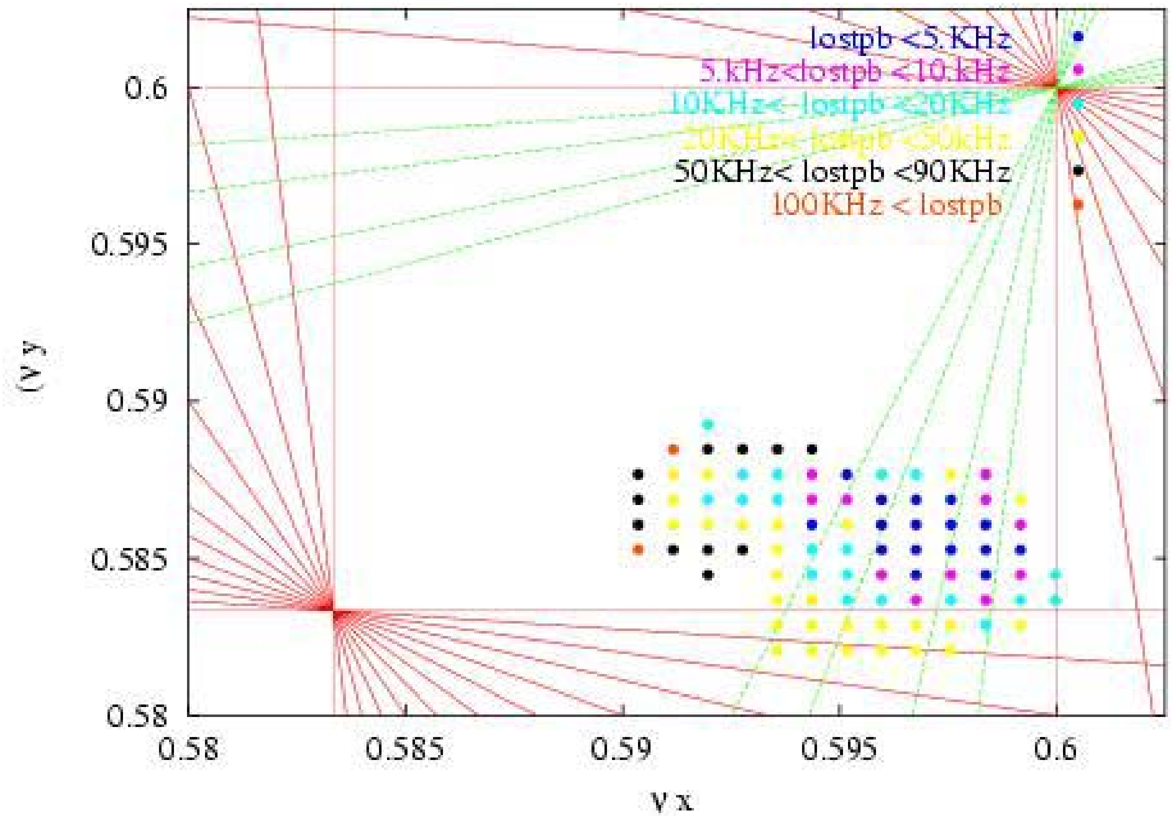
- Pbar bunches near abort gaps have better emittances and live longer
- Emittances of other bunches are being blown up to 40% over the first 2 hours – see scallops over the bunch trains
- The effect is (and should be) tune dependent - see on the right
- Recently, serious effects of pbars on protons – completely unexpected

Beam-beam Tune Shift Measurement



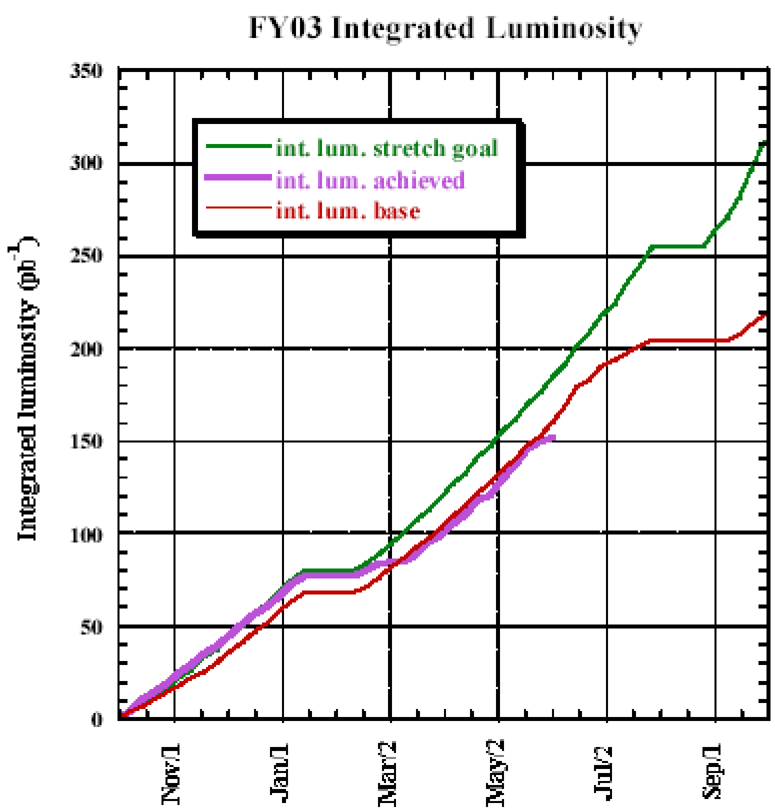
- Measured and predicted pbar tune shift as function of bunch number at collisions.
- Used gated “tickler” to excite individual pbar bunches and measured tunes with schottky pickup

Working Point Tune Scans



Measured pbar halo loss rate during collisions as function of pbar tunes

Goals for near future



- Deliver 200 – 300 pb^{-1} to each detector by end October 2003
- Steadier running (less studies)
- Reach peak luminosities of 45-50e30 be end of summer.
- 5-10% more protons
  - From MI, better in Tev
- 5-10% more pbars
  - Larger stacks
  - New helix
- 5-10% smaller emittances
  - Scallops tuned
  - Injection matching
  - Dampers

Tevatron Beam Physics Issues

- New helix
- MI -> Tev injection mismatch
- Octupoles or dampers on the ramp
- Beam-beam studies and compensation
- Tevatron BPMs, orbit smoothing
- Tevatron alignment (smart bolts and rolls)
- Lattice measurements